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OXIDIZER HEAT EXCHANGER COMPONENT TEST FINAL REPORT

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R19602/1

FOREWORD

This report summarizes the test activity and post-test data analysis for high heat transfer and low heat transfer heat exchanger designs. The heat exchangers were tested and evaluated for application to the RL10-IIB derivative multi-mode thrust engine. The work was performed in compliance with the requirements of NASA Lewis Research Center Contract NAS3-24738.

Testing was performed from 17 September to 8 December 1986. Testing was conducted and reported by Paul G. Kanic, Senior Test Engineer. The effort was headed by Thomas D. Kmiec, Project Engineer.

The following individuals have made significant contributions to the preparation of this report: Donald E. Galler, Raymond B. Kaldor, Luis J. Lago, and Ken Maynard.

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INTRODUCTION

Low thrust cryogenic rocket engine operation offers attractive advantages for space travel. These include the capability for efficient engine thermal conditioning and the availability of propellant settling thrust. Making use of a heat exchanger during low thrust operation eliminates the need for an active control system that would otherwise be necessary. The heat exchanger uses hot gaseous hydrogen from the chamber jacket discharge as shown in Figure 1 to vaporize liquid oxygen in a stable manner, i.e., with minimal pressure and/or flow oscillations. Low thrust operation is normally at one of two levels: Tank Head Idle (THI) which is at 1-2% of rated thrust, and Pumped Idle (PI), which is at 10% of rated thrust.

During Phase 3 of the RL10 Product Improvement Program (PIP), an Oxidizer Heat Exchanger (OHE) was designed, fabricated, and tested at both the component and engine levels. These activities are reported in References 1, 2, and 3. Phase 4 of the RL10 PIP included a second iteration on the OHE concept, including redesign, fabrication, and component test of two independent OHE designs. One design makes use of a low heat transfer core to promote stable oxygen vaporization, while the other uses a high heat transfer approach in combination with a volume to attenuate pressure and flow oscillations.

The test units were delivered to Pratt & Whitney in August and September of 1986. Testing took place during the period from 17 September to 8 December 1986. Further details of the test units, flow bench, data acquisition, and data analysis can be found in the body of this report.

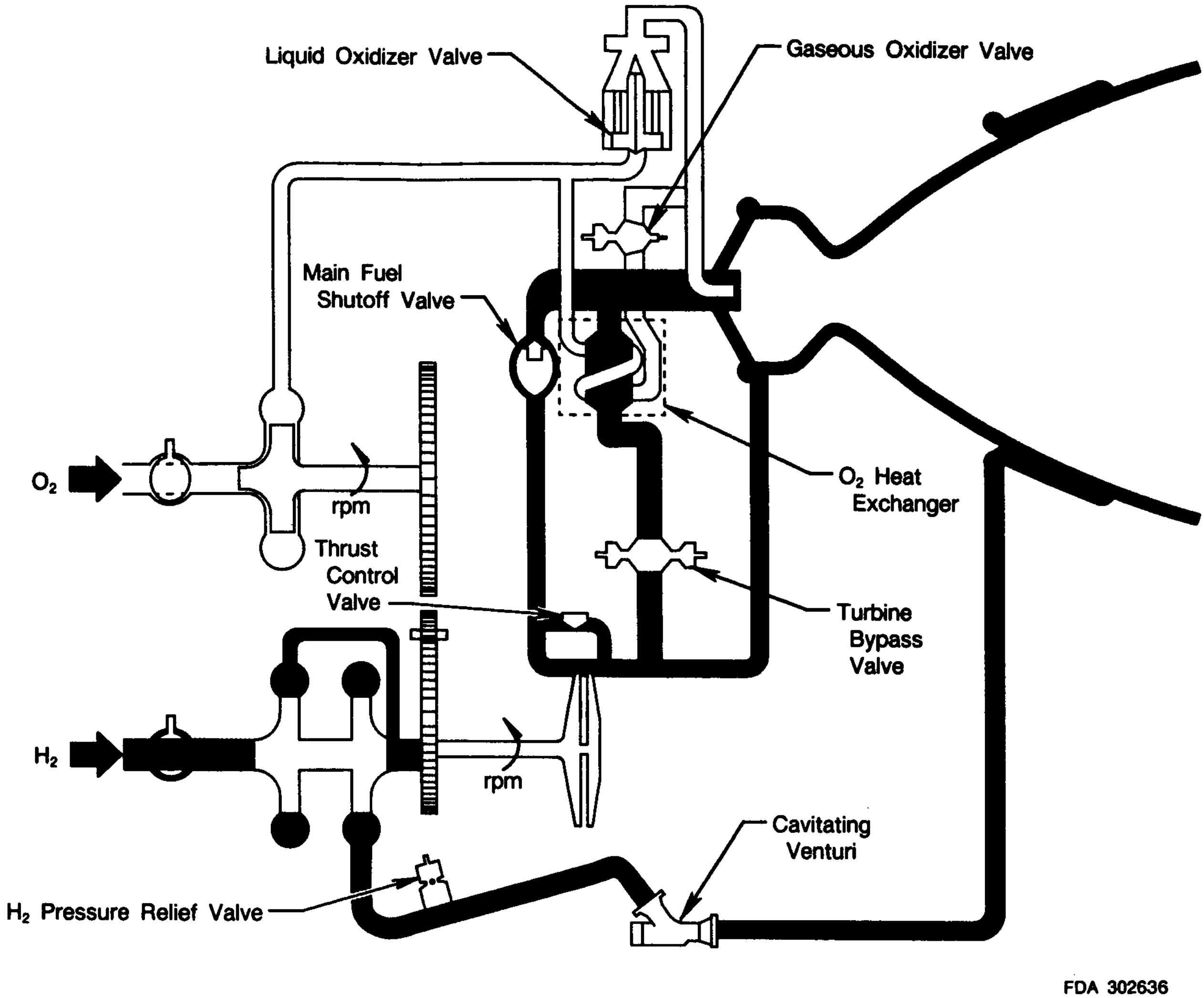


Figure 1. RL10-IIB Engine Flow Schematic

PURPOSE

Since both heat exchanger designs were new and previously untested, the series of test flows described in this report was intended to determine performance characteristics of each heat exchanger. Of particular interest was performance at the THI and PI design points, including exit quality, pressure and flow oscillations, and core pressure drops. In addition, possible internal degradation, manifesting itself as cross-circuit leakage, was monitored to determine if structural integrity was maintained during tests. The purpose of this report is to briefly describe the test items and to present in detail the test configuration, data obtained, and post-run data analysis to determine each heat exchanger's performance and suitability for engine operation.

SCOPE

This report presents all aspects of this heat exchanger performance test effort, including test bench configuration, test points, and analysis of two high heat transfer oxidizer heat exchangers and two low heat transfer oxidizer heat exchangers. The bulk of the testing was concentrated at or near the design points. Unit-to-unit repeatability was checked at the pumped idle design point only, and the effect of gravity (inversion) testing was performed at THI conditions only. This arrangement allowed the most cost-efficient determination of heat exchanger performance at the worst case conditions for each situation.

TEST ARTICLES

HIGH HEAT TRANSFER OHE

The high heat transfer OHE is a single, self-contained aluminum unit encompassing a cross-counterflow plate-fin core within a tank-shaped volume. All-aluminum construction minimizes weight while retaining favorable heat transfer characteristics. A schematic of the internal configuration with external dimensions is shown in Figure 2. Liquid oxygen enters through the bottom inlet flange and flows through a bellows into the core, where it absorbs heat from the adjacent hydrogen passages. The oxygen discharges into a volume, and exits the OHE through the discharge flange. The hydrogen enters through the inlet flange and flows through a manifold into stage 2 of the core. It then proceeds through a turnaround manifold into stage 1, discharges into the hydrogen half of the volume, and exits the OHE through the discharge flange. A complete description of the high heat transfer OHE can be found in Reference 4. Figure 3 presents a photograph of the high heat transfer OHE.

The oxygen discharge volume serves to attenuate flow oscillations by providing a damping area for pulsing expansion of gases formed by violently boiling liquid. These pulses are further reduced by the oxygen discharge flange, which serves as an attenuating orifice to the pulsing oxygen. The hydrogen volume, which is separated from the oxygen volume by a dividing plate, serves no attenuating function; it merely acts as a manifold to collect the hydrogen prior to discharge. The core is suspended within the volume by the dividing plate. Since the core is completely contained within the volume, it does not sustain the full proof pressure, resulting in a lower strength requirement with its associated weight savings.

Each high heat transfer OHE was identified as P/N P-10770 and was designed and manufactured by Alpha United, Inc. to comply with the requirements of Purchase Performance Spec (PPS) F-654. The units tested were S/N 002 and S/N 003. Each unit weighed approximately 32 lb dry.

LOW HEAT TRANSFER OHE

The low heat transfer OHE is a single, self-contained aluminum unit with a three-stage, plate-fin core of cross-counterflow configuration. Figure 4 presents a schematic of the heat exchanger with external dimensions. It was designed to meet the requirements of Purchase Performance Specification (PPS) F-654. Liquid oxygen enters through the bottom inlet flange and progresses through a manifold to the core. As the oxygen passes through stages 1, 2, and 3 of the core in a straight line, it vaporizes and exits through the discharge manifold and flange. The hydrogen enters through the inlet flange and manifold and enters stage 3 of the core. After passing through stages 3, 2, and 1 in succession, the hydrogen discharges through the exit manifold and flange. A more detailed description of the low heat transfer OHE can be found in Reference 5. A photograph of this OHE is shown in Figure 5.

To prevent violent oxygen boiloff and the associated flow instability, this heat exchanger uses a low heat flux over a large heat transfer area for gradual rather than rapid vaporization. Excessive heat transfer is prevented through the use of a resistance layer between the oxygen and hydrogen flow layers. This resistance layer is vented to vacuum, providing a thermal barrier to heat flow from the hydrogen to the oxygen.

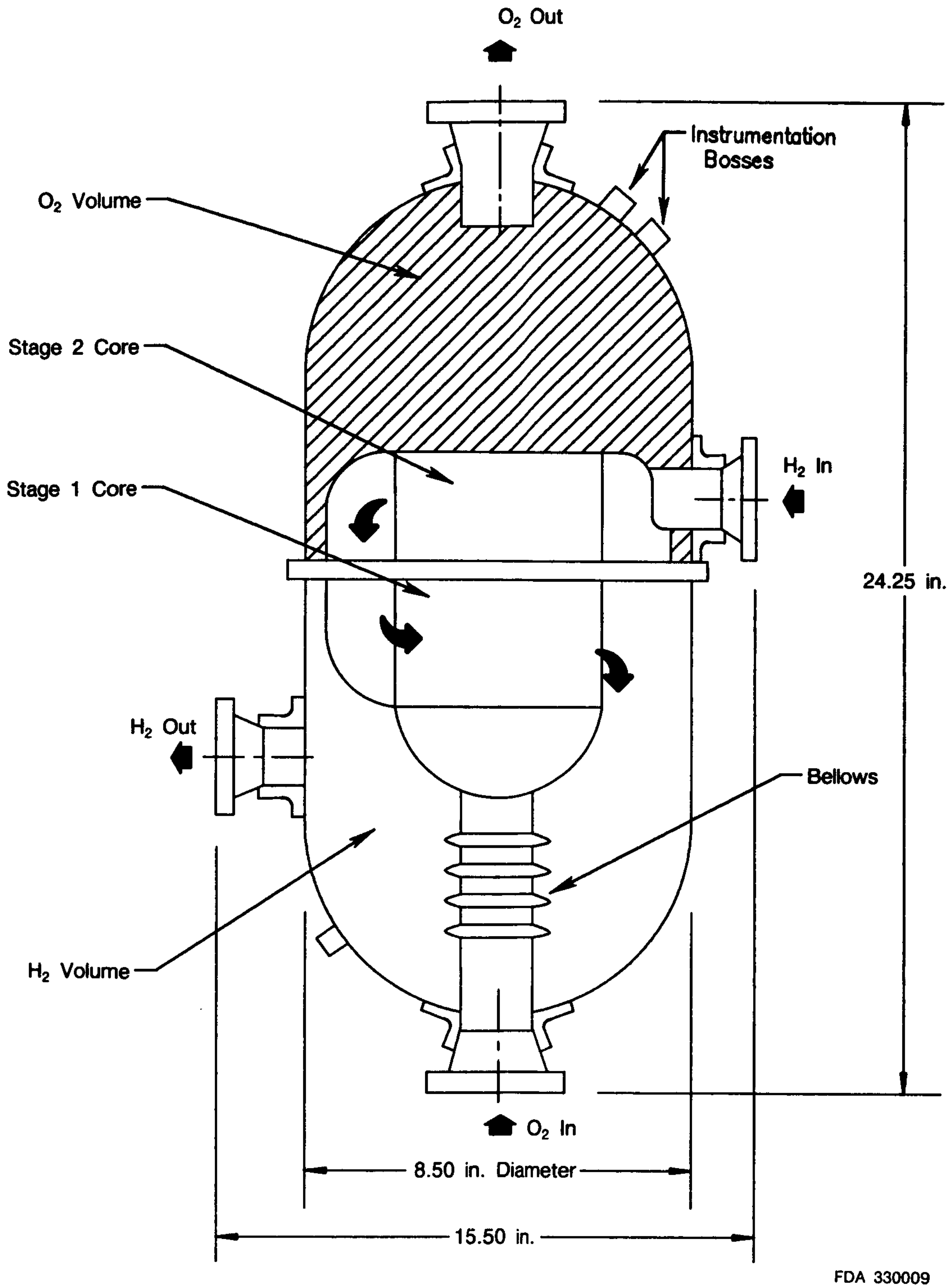
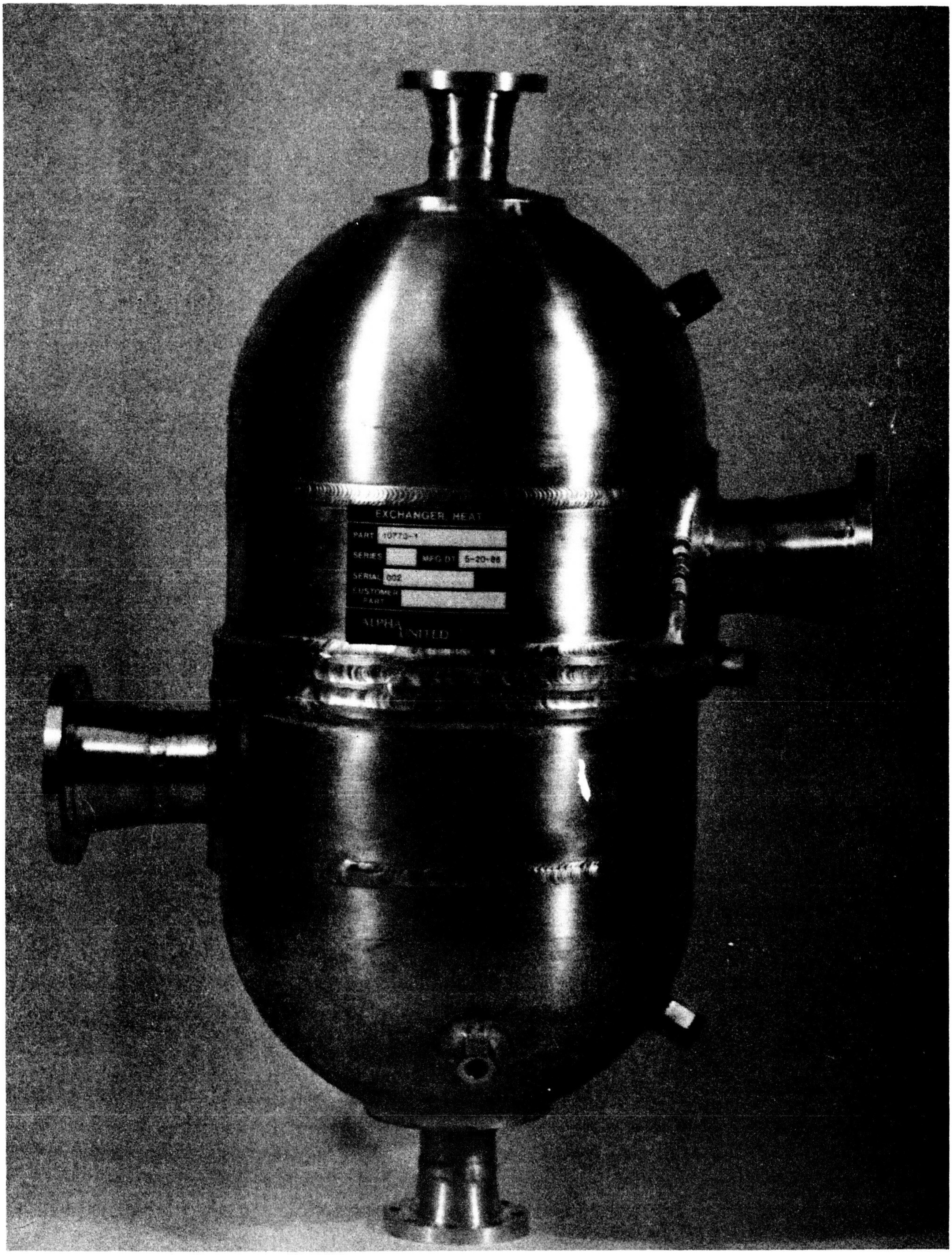


Figure 2. High Heat Transfer (AU) OHE Schematic



FC 104112-H

Figure 3. High Heat Transfer OHE

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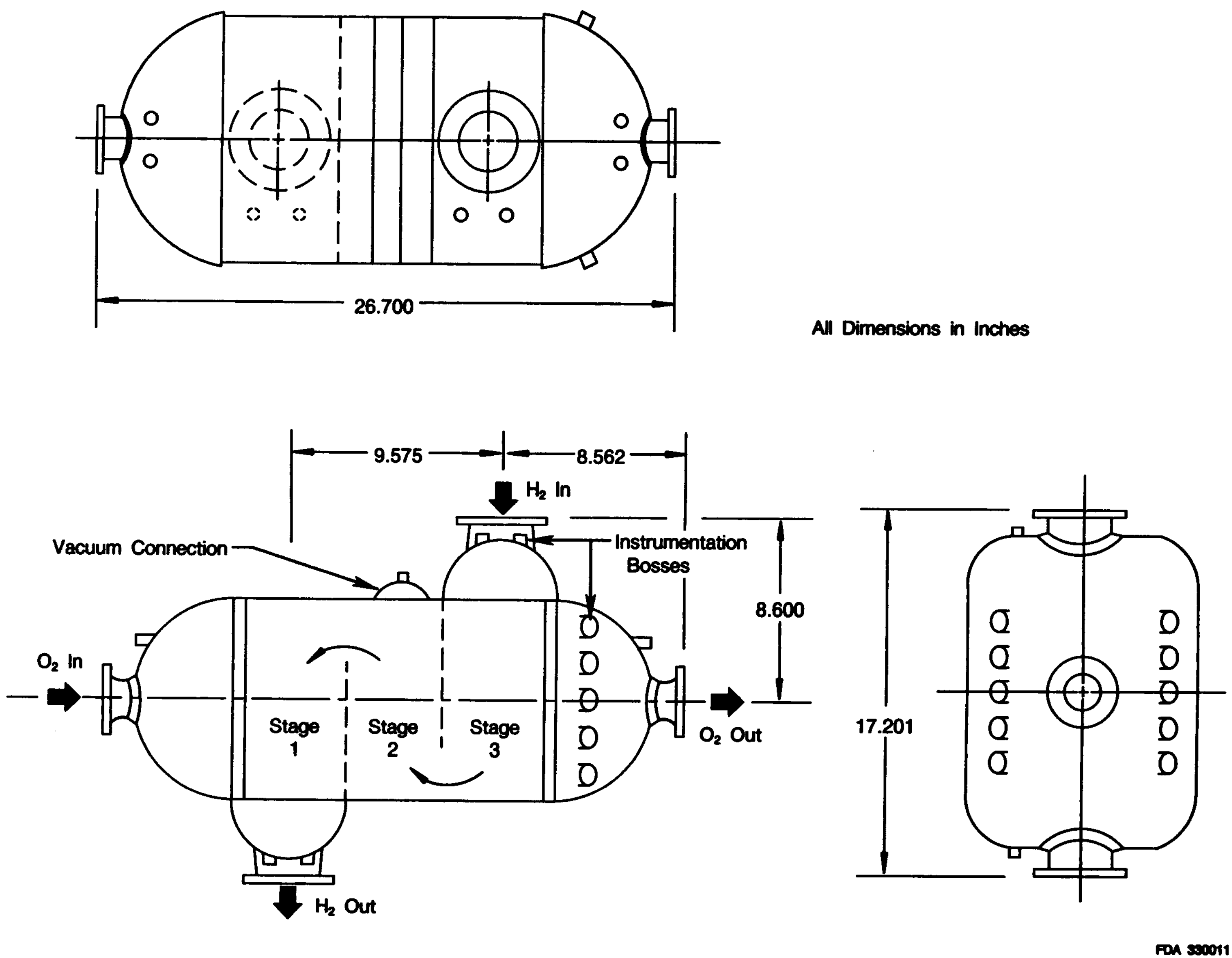
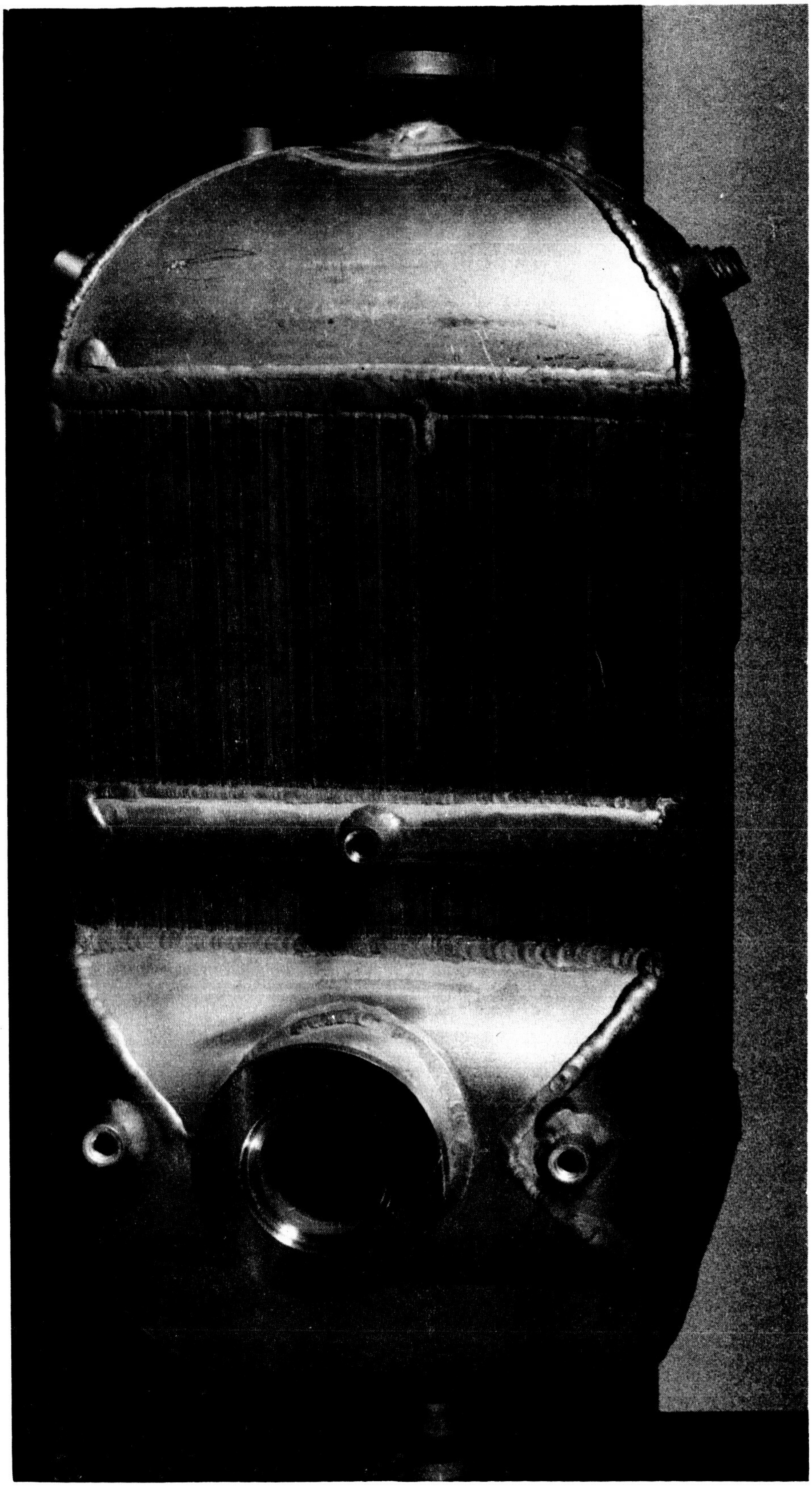


Figure 4. Low Heat Transfer (UAP) OHE Schematic



FC 104113-H

Figure 5. Low Heat Transfer OHE

Each low heat transfer OHE was identified as P/N UA538949-1 CKD10001 and was manufactured by United Aircraft Products, Inc. The units tested were S/N UAP R0001 and S/N UAP R0002. Each unit weighed approximately 64 lb dry.

FLOWBENCH CONFIGURATION

All flows took place on an E-6 stand, which is a liquid oxygen/liquid hydrogen test stand normally used to test RL10 rocket engines at high altitude conditions. Existing stand capabilities were such that relatively minor modifications were necessary to obtain conditions unique to heat exchanger testing. The stand has the capability to flow the following fluids: liquid and gaseous oxygen, liquid and gaseous hydrogen, gaseous nitrogen, gaseous helium, and air. Also, a vacuum pump is available for use with the low heat transfer OHE resistance cavity. Stand modifications to facilitate OHE testing were kept to a minimum to minimize cost impact and were structured such that engine test programs could be run concurrently if necessary.

The following additions were made to the stand to allow heat exchanger testing:

- Plumbing from the LO_2 supply line to the OHE, and from the OHE to the LO_2 dump line
- Plumbing from the GH_2 supply line to the OHE, and from the OHE to the H_2 burnstack
- Valves and pressure relief devices to allow control of fluids and provide safety
- Orifices upstream of the OHE inlets for LO_2 and GH_2 flow measurement
- Plumbing from the vacuum pump to the OHE
- Four electrical resistance element heaters providing a total of 92 kw of heat for high temperature hydrogen flows
- Stand electrical modifications to supply and control power to the heaters
- Sufficient instrumentation at various locations in the inlet and discharge lines as required by the test plan.

A flow schematic of the test stand showing plumbing routing and valve locations is shown in Figure 6.

After being cleaned for liquid oxygen service, the test item (OHE) was semi-rigidly mounted with support provided primarily by an overhead rod and turnbuckle. Fiberfrax insulation was wrapped around the OHE, the oxygen flow measurement orifice, and the LO_2 inlet line approximately fifteen feet upstream of the OHE. Aluminum foil was then used to isolate the insulation layer from ambient air.

Occasionally during testing, minor additional stand modifications were necessary to accomplish test objectives. These modifications, such as changing the location of bypass flow plumbing to facilitate stand cooldown, were made as needs were identified.

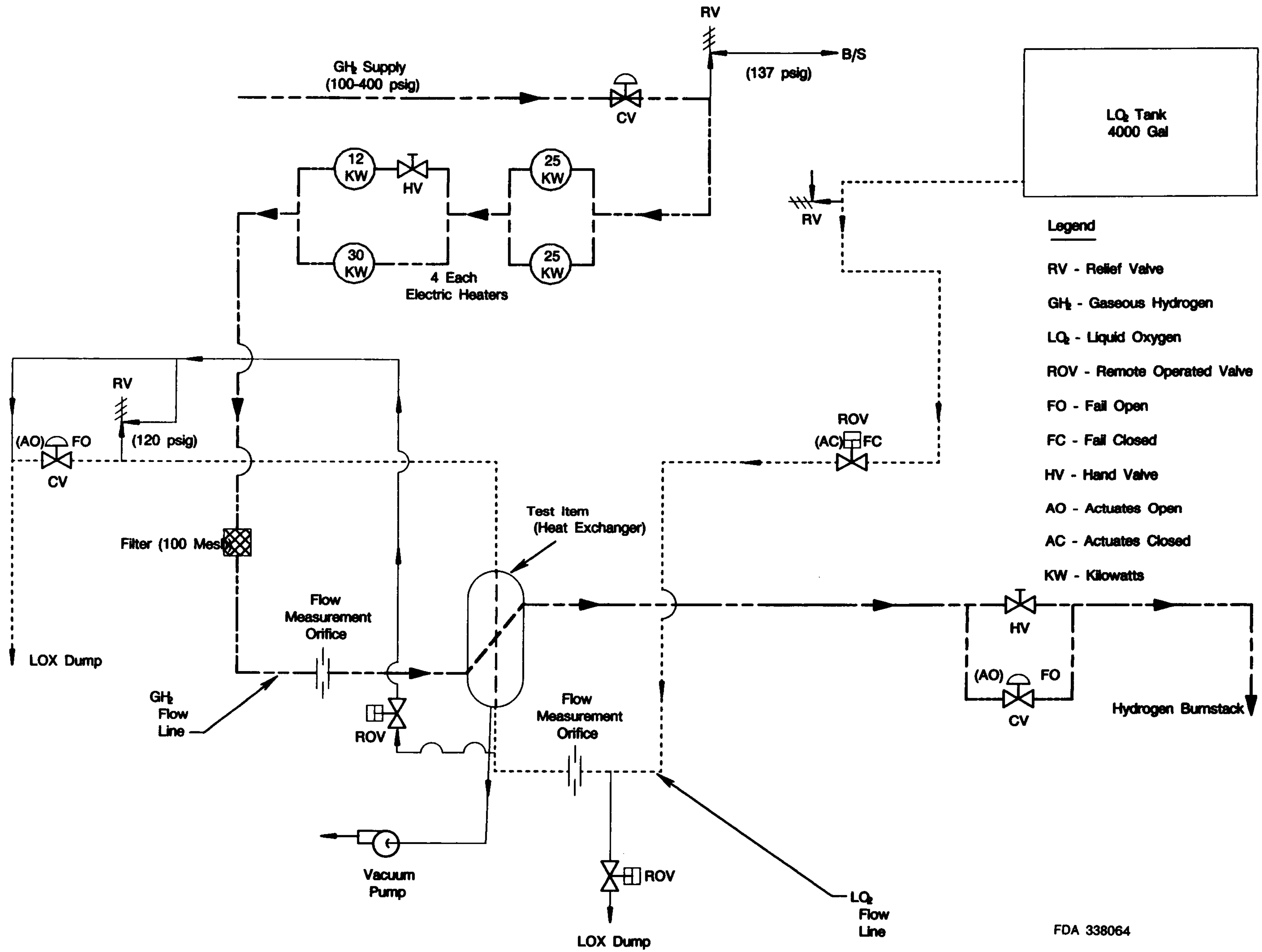


Figure 6. Test Stand Flow Schematic

TEST PROGRAM

The test program was originally intended to be as defined in the Oxidizer Heat Exchanger Performance Test Plan dated 28 January 1986 and revised 27 February 1986. The plan addressed test stand considerations, instrumentation, and the OHE inlet conditions for each of the 86 test points required for each design. Provisions for inverted OHE testing (O_2 inlet at the bottom) to determine the effects of gravity on performance were included in the plan. It also provided for testing of a second unit of each design to check for unit-to-unit performance repeatability.

Although exact test points were defined in the test plan, instability problems encountered during real-time data acquisition prevented the accurate setting of oxygen flows. Apparently, pressure pulses generated during off-design point flows were propagating back to the O_2 flow measurement orifice. The resulting large variations in the orifice differential pressure caused wildly fluctuating flow measurements, which were impossible to set with any degree of accuracy. Therefore, a range of flows near the design points were explored until stability was found. Once an area of stability was located, the limits of that stable area could be explored. The test points obtained reflect this approach.

An intermediate range of flows was outlined in the test plan; however, since there were no design points in this range, and given the difficulty in setting the oxygen flows, the additional effort of testing in this area was not justified by the resultant limited additional information.

RUN SUMMARY

HIGH HEAT TRANSFER OHE

The first high heat transfer OHE S/N 002 was mounted in E-6 stand on 4 September 1986 and was identified as Rig F-33045. Following installation of temperature probes and pressure transducers, a complete leak check of the entire system was completed. A test flow through the LO_2 and GH_2 circuits was performed on 11 September, followed by a repeat leak check. After rectifying instrumentation problems and verifying that the data recording system was operating properly, flows were begun. On this unit, PI and THI areas of stability were investigated with the OHE oriented such that the O_2 inlet was from beneath. The high heat transfer heat exchanger is shown mounted in the test stand in Figures 7 through 9.

The second high heat transfer OHE S/N 003 was mounted in E-6 stand on 4 December 1986 and was identified as Rig F-33048. The second unit was used primarily to check unit-to-unit performance repeatability and to investigate OHE performance while operating in an inverted position.

The following is an accounting of each flow and the prime objectives accomplished.

Rig F-33045 9/4/86 — *High heat transfer OHE S/N 002 OHE mounted in E-6 stand.*

Flow 1.01 9/11/86 — *Checkout flow to cold shock stand system and leak check connections. All leaks found and repaired.*

Flow 1.02 9/17/86 — *Planned PI test points were to be run. While trying to set OHE inlet conditions, the LO_2 tank rupture disk blew. Shutdown flows to replace disk.*

Flow 1.03 9/18/86 — *Planned PI test points were to be run. At the high GH_2 flows, the needed OHE H_2 inlet temperature was not reached. Shutdown flows to increase heater thermostat levels.*

Flow 1.04 9/18/86 — *Planned PI test points were to be run. While attempting to set the first point, had OHE oxygen inlet pressure abort. Recycled abort system and attempted to continue. Repeated OHE oxygen inlet pressure abort. Apparently, violent boiling was taking place as the hot hydrogen contacted the OHE, which was filled with LO_2. Since the LO_2 control valve downstream of the OHE was nearly closed for the lower lox flows, pressure pulses were propagating back through the OHE inlet, activating the abort.*

Since this situation did not approximate actual engine conditions, the sequence in which flows were introduced to the OHE was changed. Instead of initially flowing LO_2 through the entire system, a bypass was installed at the OHE inlet, and LO_2 flow was permitted only up to the OHE inlet. After the hydrogen conditions were set, LO_2 flow would be introduced through the heat exchanger.

Also, oxygen instability caused large oscillations in the flow readings, making it impossible to set oxygen flow conditions. As a result, it was necessary to deviate from the test plan and pursue an alternate plan to investigate a range of flows near the PI conditions in an effort to locate an area of stability. This was done by gradually opening the downstream oxygen control valve in intervals to provide test points with gradually increasing oxygen flows.

Flow 1.05 9/23/86 — *Investigative range of test points in the PI range were to be run. PI points No. 90 through No. 99 were recorded in addition to slow speed (2 scans/second) transient data. These points were taken as the downstream oxygen control valve was opened in intervals from full closed to full open.*

Flow 1.06 9/23/86 — *Investigative range of test points in the PI range near the area of stability found in Flow 1.05. Points No. 100 through No. 108 were recorded. The limits of stability were investigated during this flow.*

Flow 1.07 9/24/86 — *Investigative range of test points in the THI range. Points No. 109 and No. 110 were recorded. Some problems were experienced in cooling down the O_2 inlet line sufficiently to provide liquid at the OHE inlet. This was traced to instrumentation discrepancies which were corrected for the next flow. Also, preliminary post-run data indicated insufficient time was allowed for thermal stabilization between points.*

Flow 1.08 9/24/86 — *Investigative range of test points in the THI range. Points No. 111 through No. 120 were recorded. Additional time was allowed between points to ensure all thermal transients were complete and a steady-state condition had been achieved.*

10/2/86 — *High heat transfer OHE S/N 002 was dismounted from E-6 stand.*

Rig F-33048 12/4/86 — *High heat transfer OHE S/N 003 OHE mounted in E-6 stand*

Flow 1.01 12/5/86 — *Pumped idle flows for repeatability check were run. Points 30 through 47 were recorded. A range of PI flows was made and a single additional point from the previous high heat transfer OHE was duplicated to enable a direct one-on-one comparison of PI conditions for the repeatability check.*

Flow 1.02 12/8/86 — *Tank head idle flows were run with the OHE inverted such that the O_2 inlet was on the top. A range of flows and conditions were explored in an effort to locate an area of stable operation. Points 50 through 53 were recorded. Flow and pressure measurements indicated some poorly defined areas of limited stability. It appeared that O_2 gas produced when the liquid droplets contact the OHE core were rising back up through the inlet tube and propagating back to the O_2 flow measurement orifice.*

Flow 1.03 12/8/86 — *Repeat of Flow 1.02, except an off-scale temperature measurement was corrected. Points 54 through 60 were recorded.*

12/12/86 — *High heat transfer OHE S/N 003 was dismounted from E-6 stand.*

LOW HEAT TRANSFER OHE

The first low heat transfer OHE S/N UAP R0001 was mounted in E-6 stand on 6 October 1986 and was identified as Rig FR-33046. Temperature probes and pressure transducers were installed in the OHE, followed by an instrumentation and recording system checkout. After leak checks were completed, flows were begun. The low heat transfer heat exchanger is shown mounted in the test stand in Figures 10 through 12.

The second low heat transfer OHE S/N UAP R0002 was mounted in E-6 stand on 19 November 1986 and was identified as Rig F-33047. The second unit was used primarily to check unit-to-unit performance repeatability and to investigate OHE performance while operating in an inverted position. The following is an accounting of each flow and the primary objectives accomplished.

Rig FR-33046 — *Low heat transfer OHE S/N UAP R0001*
10/6/86 *OHE mounted in E-6 stand.*

Flow 1.01 — *Investigative range of test points in the THI range. Points No. 130*
10/7/86 *through No. 139 were recorded.*

Flow 1.02 — *Investigative range of test points in the PI range. Points No. 140*
10/8/86 *through No. 155 were recorded. Due to a condition similar to the high heat transfer OHE, violent boiling caused oxygen flow oscillations of sufficient magnitude to preclude setting test points. Therefore the downstream oxygen control valve was again gradually opened in intervals while test points were recorded, in an effort to search for a stable operating area.*

Flow 1.03 — *Repeat of Flow 1.02. Recorded points No. 156 - No. 161.*
10/8/86

10/13/86 — *Low heat transfer OHE S/N UAP R0001 was dismounted from E-6 stand.*

Rig F-33047 — *Low heat transfer OHE S/N UAP R0002*
11/19/86 *OHE mounted in E-6 stand*

Flow 1.01 — *Pumped idle flows for repeatability check run. Points 1 through 16*
12/2/86 *were recorded. A range of pumped idle flows were made and a single additional point from the previous low heat transfer OHE was duplicated to enable a direct one-on-one comparison of PI conditions for the repeatability check.*

Flow 1.02 — *Tank head idle flows were made with the OHE inverted such that*
12/3/86 *the O_2 inlet was on the top. A range of flows and conditions were explored in an effort to locate an area of stability. Points 17 through 22 were recorded. No areas of stability were found. It appeared that O_2 gas produced when liquid droplets contacted the OHE core were rising up through the inlet tube and propagating back to the O_2 flow measurement orifice.*

12/4/86 — *Low heat transfer OHE S/N UAP R0002 was dismounted from E-6 stand.*

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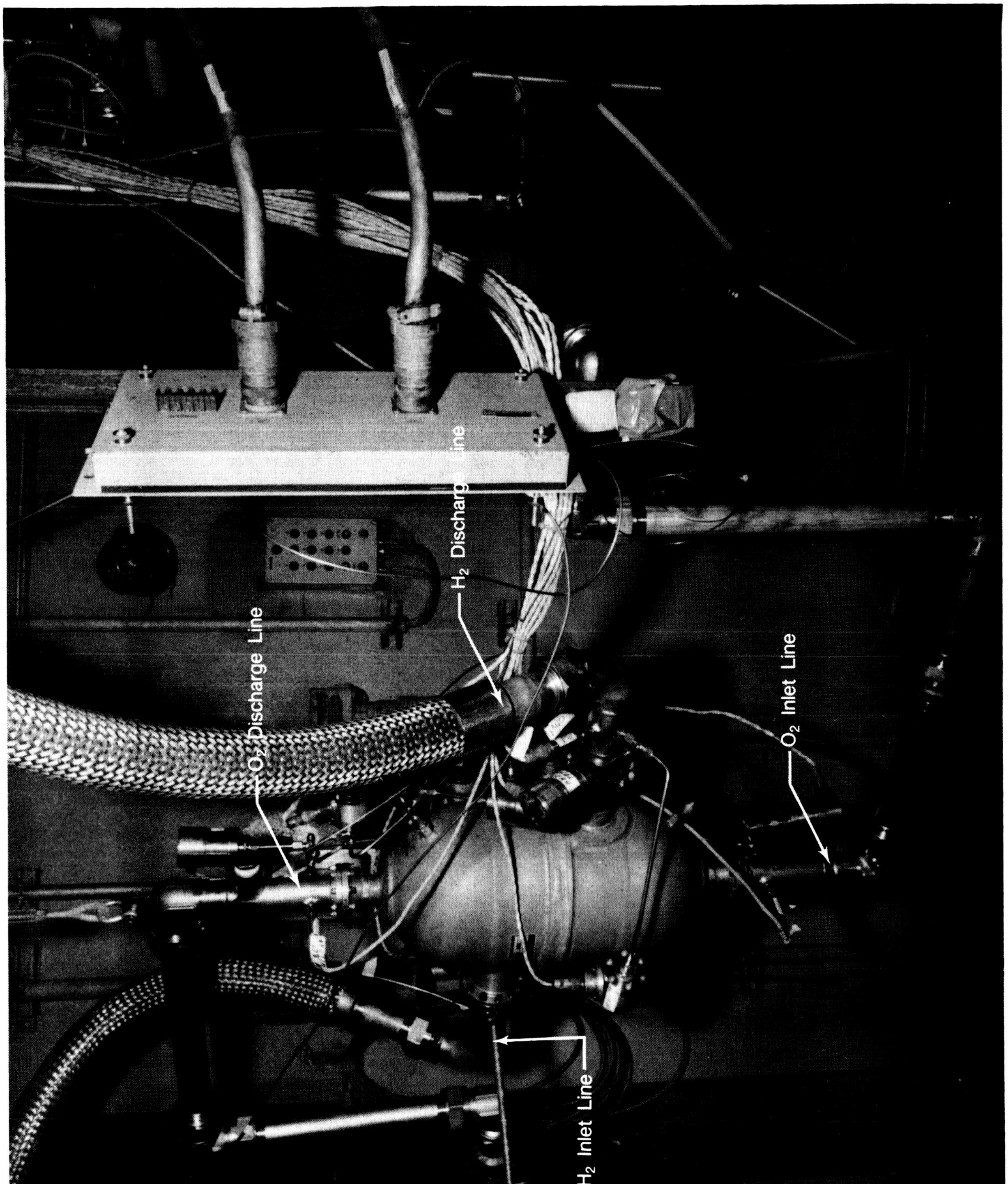

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Figure 7. High Heat Transfer OHE Mounted in E-6 Stand (Left Side View)

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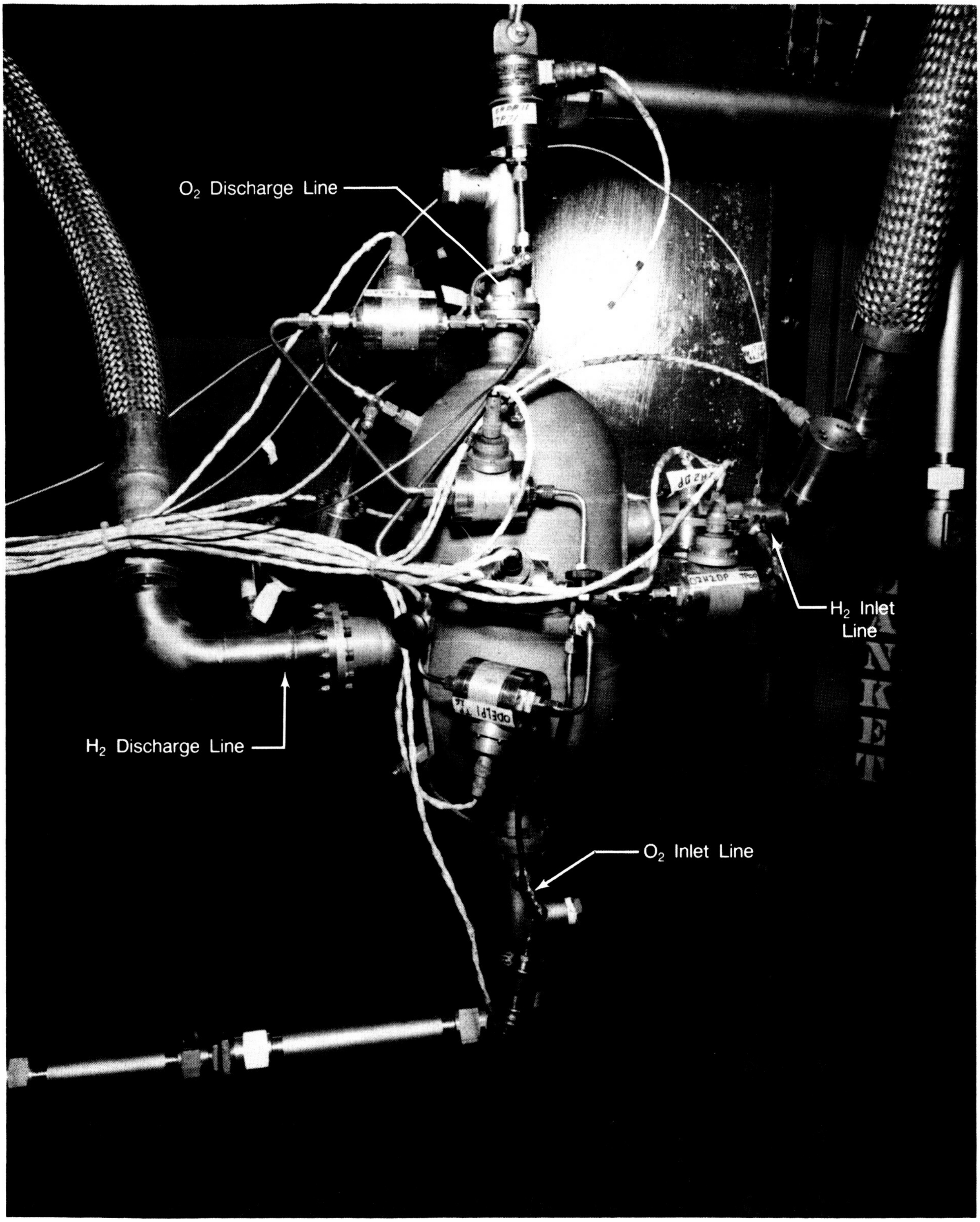

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Figure 8. High Heat Transfer OHE Mounted in E-6 Stand (Right Side View)

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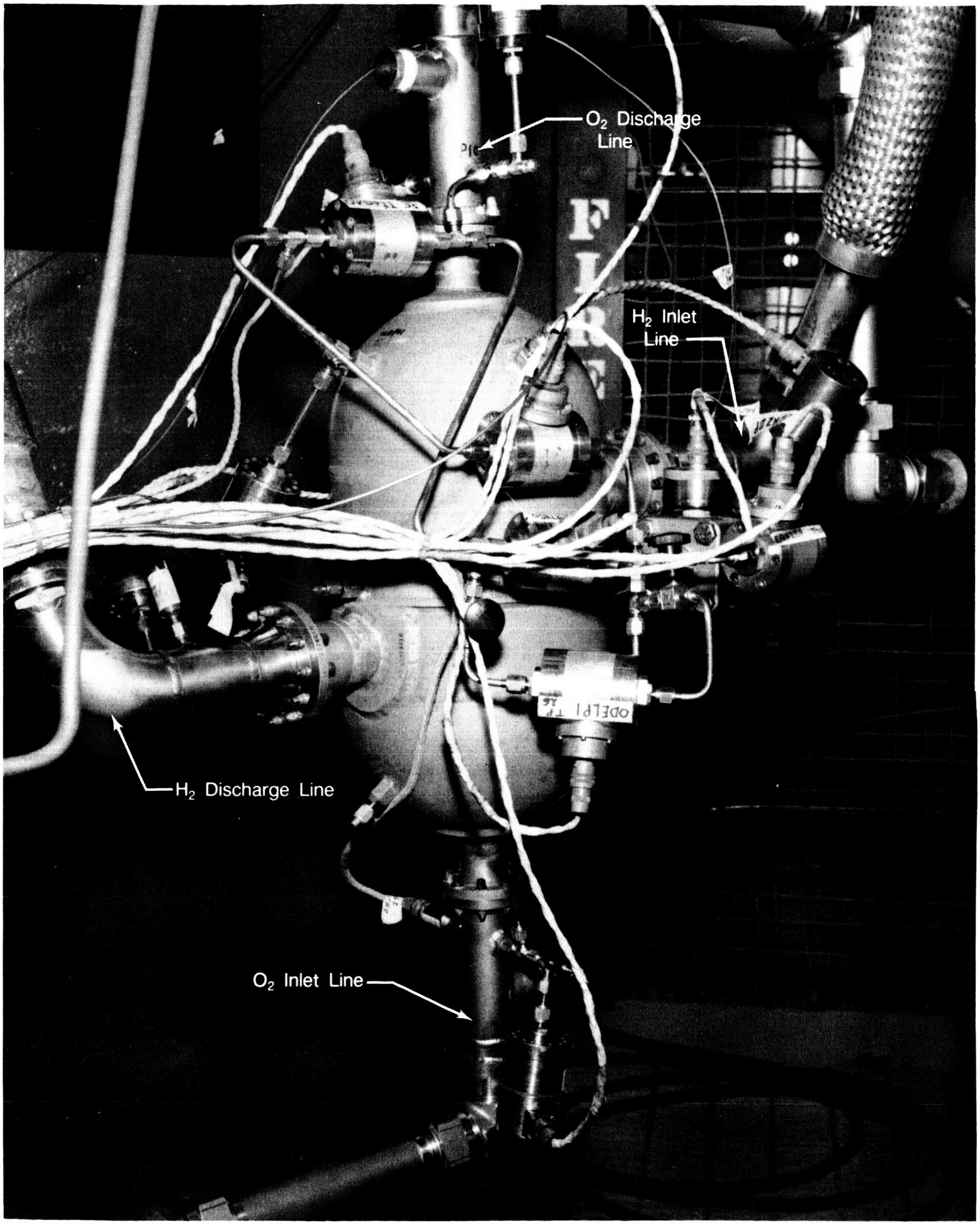

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Figure 9. High Heat Transfer OHE Mounted in E-6 Stand (Front View)

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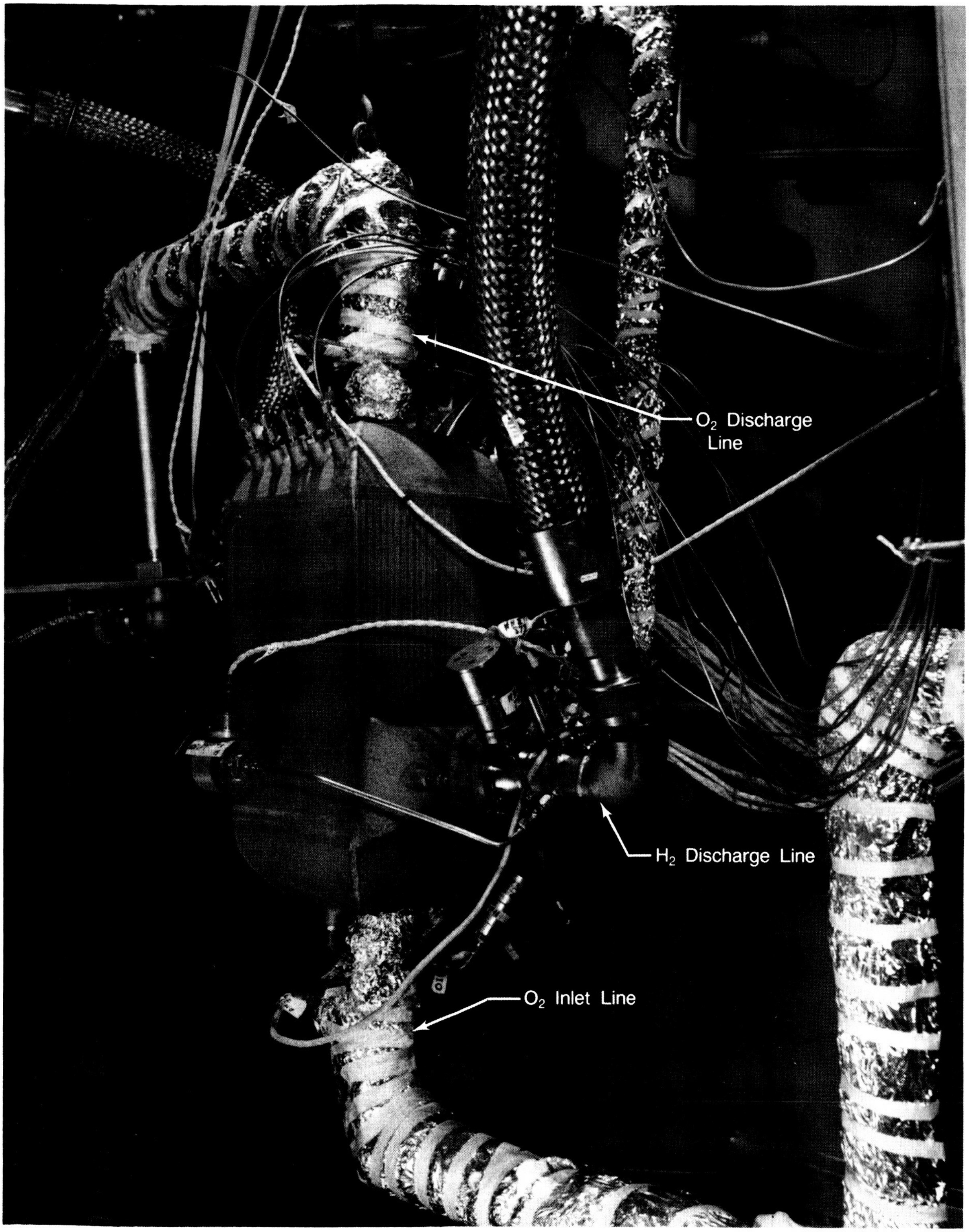

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Figure 10. Low Heat Transfer OHE Mounted in E-6 Stand (Front View)

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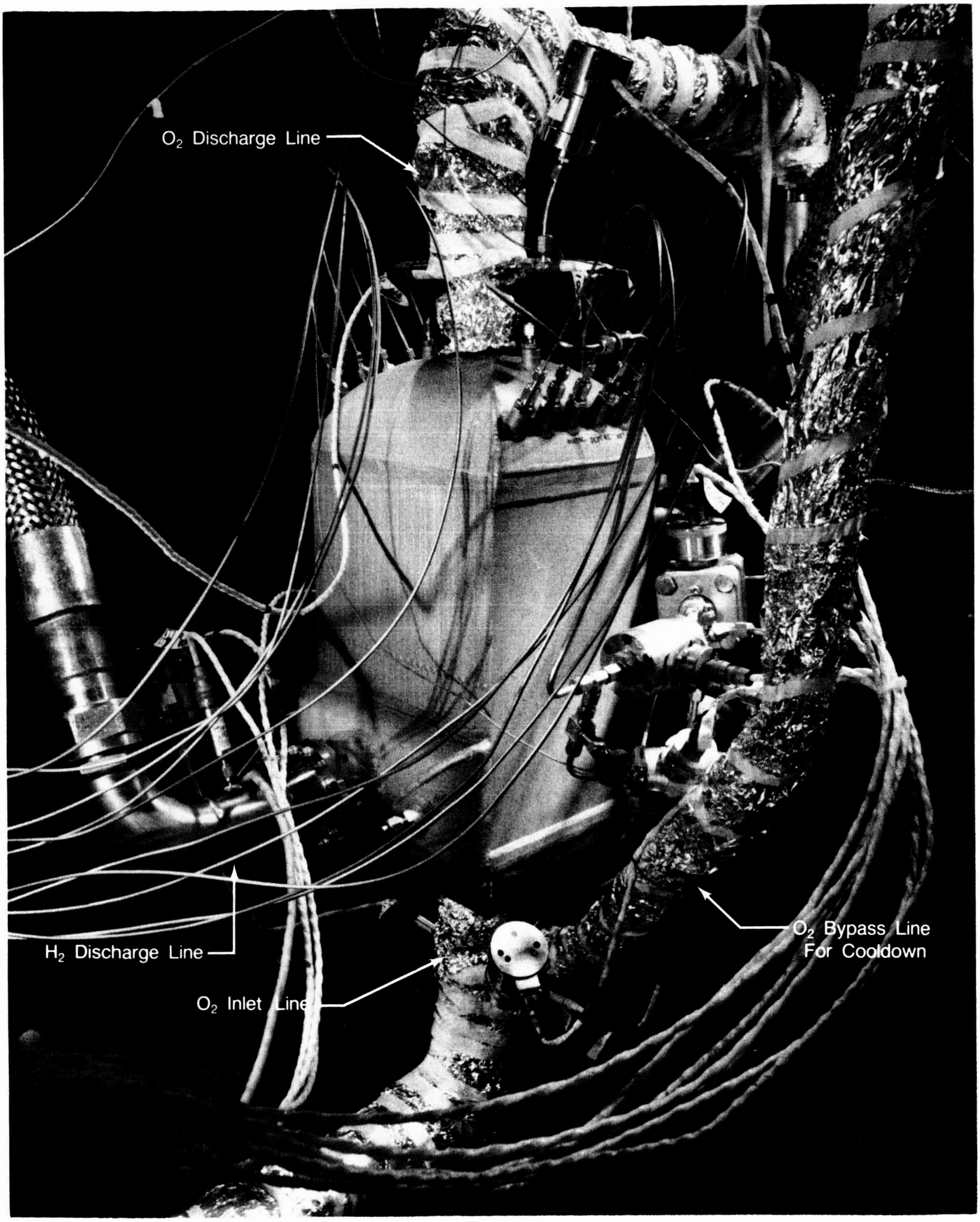

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Figure 11. Low Heat Transfer OHE Mounted in E-6 Stand (Right Side View)

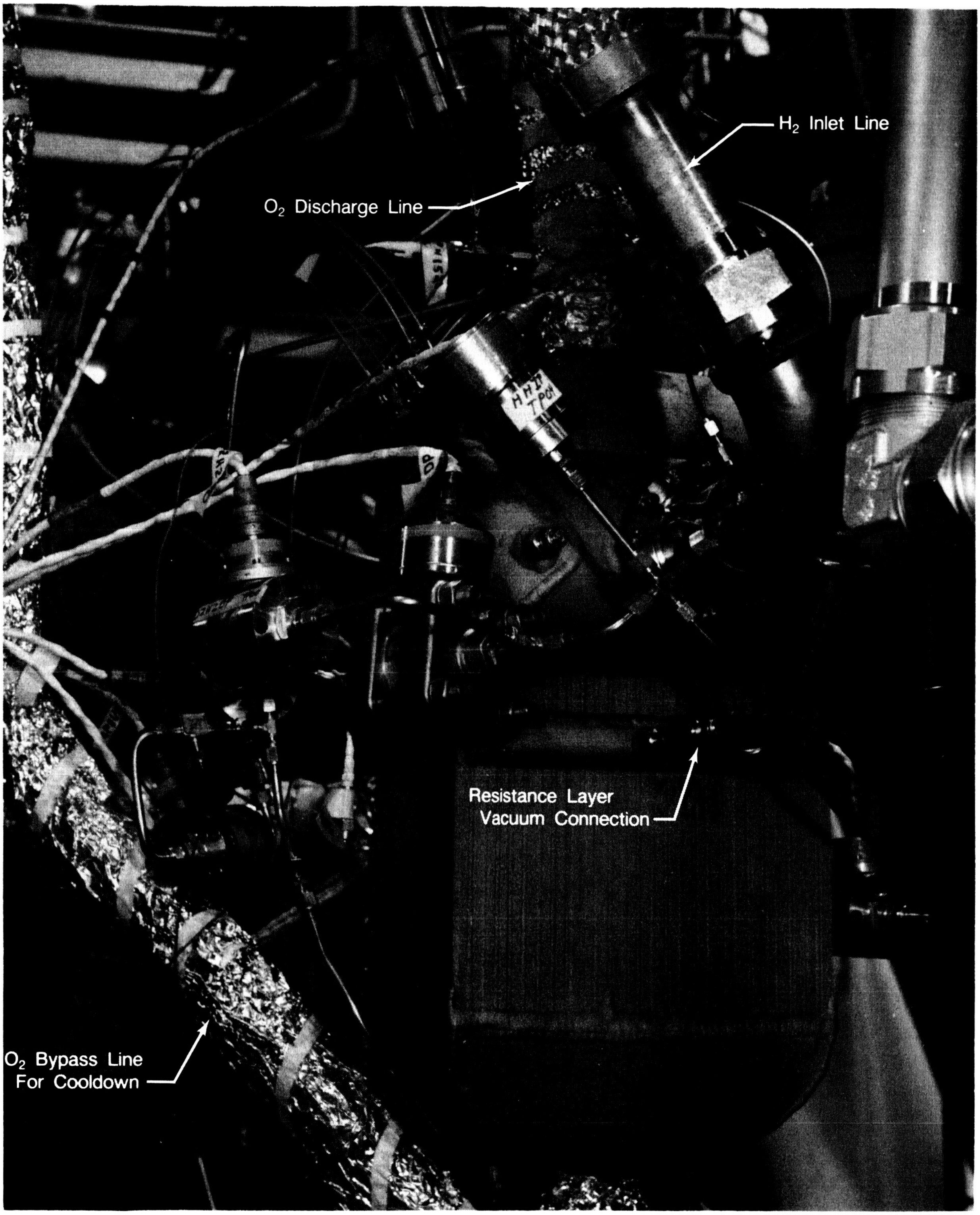

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Figure 12. Low Heat Transfer OHE Mounted in E-6 Stand (Left Side View)

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CROSS-CIRCUIT LEAKAGE TESTS

Any leakage which allows hydrogen and oxygen to come in contact with each other is of primary concern in the OHE. Therefore, leakage checks were conducted as a safety measure and also as a method of monitoring the internal structural integrity of the OHE. A baseline leakage measurement was obtained before cold flows began, and additional measurements were taken on every day that flows took place.

The leakage measurement procedure was as follows:

> O_2 circuit to H_2 circuit — A GN_2 pressure source was connected to the O_2 circuit. A leakage measurement device was connected to a port in the H_2 circuit while the remaining H_2 ports were capped. A 100 psig GN_2 pressure was applied and maintained for 5 minutes, after which a measurement was taken.
>
> H_2 circuit to O_2 circuit — Same as above, except the pressure source was connected to the H_2 circuit and the leakage measurement device was connected to the O_2 circuit.

The procedure was the same for both heat exchanger designs. A summary of the leakage test results is shown in Table 1. Although one high heat transfer heat exchanger did exceed the 10 sccm OHE specification limit, at no time were any of the measured leakage rates considered to be a safety hazard.

Since leakage rates did not increase between runs, structural degradation due to thermal and pressurization cycles did not appear to pose a problem.

Table 1. *OHE Cross-Circuit Leakage Check Summary*

High Heat Transfer OHE			*Leakage (SCCM)*
S/N 002	9/11 (Baseline)	$H_2 \rightarrow O_2$	4.5
		$O_2 \rightarrow H_2$	6.0
	9/17	$H_2 \rightarrow O_2$	4.0
		$O_2 \rightarrow H_2$	2.0
	9/18	$H_2 \rightarrow O_2$	5.0
		$O_2 \rightarrow H_2$	6.5
	9/23	$H_2 \rightarrow O_2$	4.5
		$O_2 \rightarrow H_2$	6.0
S/N 003	12/4 (Baseline)	$H_2 \rightarrow O_2$	100
		$O_2 \rightarrow H_2$	100
	12/5	$H_2 \rightarrow O_2$	100
		$O_2 \rightarrow H_2$	100
	12/12	$H_2 \rightarrow O_2$	100
		$O_2 \rightarrow H_2$	100
Low Heat Transfer OHE			
S/N UAP R0001	10/6 (Baseline)	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0
	10/7	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0
	10/8	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0
S/N UAP R0002	12/1 (Baseline)	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0
	12/2	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0
	12/3	$H_2 \rightarrow O_2$	0
		$O_2 \rightarrow H_2$	0

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PERFORMANCE ANALYSIS

GENERAL

Two basic assumptions were made in the OHE performance analysis approach. These were:

1. All of the heat provided by the hydrogen was transferred to the oxygen. This assumption was made because the hydrogen temperature was near the ambient test cell temperature, minimizing the possibility of external heat leak. Also, insulation around the OHE acted as an additional barrier to unintended heat flow.

2. Oxygen entered the OHE in a liquid state (saturated or subcooled) and discharged from the OHE in a gaseous state (saturated or superheated). A large discrepancy between heat rejected by the hydrogen and heat accepted by the oxygen for certain analyzed points indicated that either the oxygen entering the OHE was not all liquid or the oxygen leaving the OHE was not all gas. Examination of other data could usually isolate the cause to one of these two reasons. The data could then be interpreted accordingly.

By adding the oxygen enthalpy rise (determined from the hydrogen heat flux per assumption No. 1) to the inlet enthalpy, the exit quality could be determined for any two-phase flow situations discovered while applying assumption No. 2. In such instances, this process was used because pressure and temperature values alone are not sufficient to determine exit quality for two-phase flow. A complete explanation of the analysis methodology is in the discussion section of Appendix A. Pressure drop information was directly available from the OHE instrumentation.

The actual flows deviated from the original test plan due to unanticipated instability problems. This prompted investigation of a range of flows in search of an area of stability. As test data points were recorded throughout this process, many points showed instability associated with violent oxygen boiling. The stable points provided the most useful data, and stability at the pumped idle points was concentrated primarily near the design points for both heat exchanger designs. Tank head idle performance for both designs was stable at all flows with the OHE in the upright position. Of course, since the primary areas of interest are at the THI and PI design points, the bulk of the analysis was concentrated there.

Specific data and performance analyses are presented in Appendixes A, B, and C. Appendix A presents data and evaluates performance of the first high heat transfer unit (S/N 002) and the first low heat transfer unit (S/N UAP R0001). This analysis was limited to tank head idle and pumped idle points with the test units in the upright position, and liquid oxygen entering from below. Appendix B presents data and discussion of the performance of the second units of each design (high test transfer unit S/N 003 and low heat transfer unit (S/N UAP R0002) with specific attention given to unit-to-unit repeatability and performance while inverted (oxygen entering from the top).

Appendix C presents a comprehensive discussion of all heat exchanger testing and data obtained. In this analysis, particular emphasis is placed on the heat transfer characteristics of each heat exchanger design.

REFERENCES

1. Design and Analysis Report for the RL10-IIB Breadboard Low Thrust Engine, Final Report No. FR-18046-3, 12 Dec 1984.

2. Oxidizer Heat Exchanger Component Testing, Final Report No. FR-19134-3, NASA Report No. CR-179487, August 1986.

3. Breadboard RL10-IIB Low Thrust Operating Mode Final Test Report, Final Report No. FR-18683-2, NASA Report No. CR-174914, 6 Oct 1986.

4. High Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report, Final Report No. 19289-2, NASA Report No. CR-179596, May 1987.

5. Low Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report, Final Report No. FR-19135-2, NASA Report No. CR-179488, 30 January 1987.

APPENDIX A

Internal Correspondence

UNITED TECHNOLOGIES
PRATT & WHITNEY

Engineering Division

To: D. E. Galler
From: Ken Maynard
Subject: Oxidizer Heat Exchanger Test Analysis
Date: November 7, 1986
Copy To: W. M. Adamski, J. R. Brown, R. R. Foust, P. G. Kanic, T. D. Kmiec, C. D. Limerick, R. J. Peckham, C. W. Ring, R. H. Wright, File

Reference: "Oxidizer Heat Exchanger Performance Test Plan", P.G. Kanic to T. D. Kmeic, 2/27/86

SUMMARY

An Oxidizer Heat Exchanger (OHE) will be incorporated in the RL10-IIB multi-mode low thrust engine. The heat exchanger uses gaseous hydrogen to vaporize liquid oxygen prior to injection into the thrust chamber. Two flight rated designs for this heat exchanger completed testing 10/8/86. Both designs successfully vaporized the LOX while maintaining oxidizer side stability, but exceeded the desired pressure loss. The effect of this increased pressure loss will be investigated with steady-state simulation of the engine.

DISCUSSION

The OHE is required on the RL10-IIB to provide stable vaporized oxygen flow to injector when operating in the low thrust modes of pumped idle (PI) and tank head idle (THI). Without the OHE, liquid oxygen flow develops very low pressure drops across the injector leading to combustion instability. Energy from the gaseous hydrogen at the jacket discharge is used to vaporize the oxygen. In the PI mode the heat exchanger is required to produce a quality of 0.95 or greater at the oxidizer side exit. In the THI mode the oxygen should be fully vaporized. During full thrust operation the OHE provides gaseous oxygen for tank pressurization.

Two designs where tested to evaluate performance and determine which to use on the testbed engine. One design is from United Aircraft Products, Inc. and uses a low heat transfer (LHT) approach to slowly increase oxygen energy above 5% vapor and avoid the severe oscillations associated with nucleate boiling. The other OHE comes from Alpha United, Inc. and uses a high heat transfer (HHT) approach. The HHT design incorporates an integral downstream volume to damp oscillations caused by the rapid vaporization.

The analysis approach used assumed all the heat flux from the hydrogen was transferred to the oxygen. This assumption proved adequate for the test purposes when the heat flux calculations from both sides were compared. This comparison was valid for stable points where the oxygen was fully vaporized. The heat exchangers were well insulated so that outside heat input was negligible. The heat flux was calculated by knowing the hydrogen inlet and exit conditions along with flowrate. Then using the oxygen inlet conditions, flowrate, and hydrogen heat flux, the oxygen enthalpy rise was calculated. The quality was determined using an oxygen property call on exit pressure and calculated exit enthalpy. This approach was taken because there is no way of determining oxygen quality for two-phased flow from just pressure and temperature measurements. Oxygen exit measurements were used to determine heat flux for steady flow points where the hydrogen heat flux was sufficient to vaporize the oxygen. Then a comparison of heat transfer could be made. The hydrogen side measurements, and thus the hydrogen heat flux calculations, were considered to be more reliable than the oxygen side. This was because:

1. The hydrogen was gaseous throughout, allowing consistent flow calculations, temperature, and pressure measurements.
2. Unreliability on the oxygen exit measurements due to two-phased flow.
3. The oscillations in oxygen flow at certain flowrates due to the stand configuration.
4. The difficulty in getting liquid oxygen at the heat exchanger inlet due to stand limitations.

The hydrogen side effective area was calculated using the flow parameter associated with a particular pressure ratio. The oxygen side effective area was approximated for the stable flow points using the pressure drop and an average density across the heat exchanger.

Table 1 shows all test points run for the HHT design. For the reasons listed above stable test data was limited. Also, the oxygen inlet pressure was limited to 90 psia by of the test stand, therefore the 110 psia inlet pressure specification for PI operation could not be obtained. The HHT design PI test point 105, shown in Table 2, provided stable flow and agreement between hydrogen and oxygen heat flux. This point shows that the oxygen was vaporized. However, the pressure losses on both sides were approximately twice the requirements. Design point hydrogen flowrate for THI was unavailable however, good performance was obtained with design point oxygen flow while hydrogen flow was both below (test point 116) and above (test point 119) the design point flowrate. The pressure drop on the oxidizer side was well within the requirement. Table 2 shows test points 116 and 119 along with the design point specifications.

Table 3 shows results of the LHT design in the THI and PI modes. THI test point 138 shows flowrates near design on the hydrogen side but exceeds the requirement on the oxygen side. Despite the increased flow the oxygen was fully vaporized. The pressure loss on the hydrogen side was within the specification while the oxygen side, with the high flowrate, exceeded the specification slightly. PI test point 156 was near design specifications and indicated that the oxygen was vaporized. This was considered a good data point because the oxygen flow was stable and both heat flux calculations agreed. Again, the hydrogen side pressure drop was within specification while the oxidizer side was not. Table 4 shows these points separately along with the specification requirements.

Tables 5 and 6 show the heat exchanger oxygen discharge pressure oscillations of both heat exchanger designs. The source of the oscillations was not the heat exchangers but the difficulty in stabilizing the flow upstream of the heat exchangers. It can be seen at points where the flow conditions were steady that the heat exchangers maintained the the oxidizer side stability.

CONCLUSIONS

For the United Aircraft Product, Inc. LHT design the data is conclusive and shows that the heat exchanger meets the requirements on oxygen exit quality of 0.95 or greater in both the PI and THI modes while maintaining stability. This design meets the pressure loss requirement on the hydrogen side in both operating modes but exceeds it on the oxygen side during PI operation.

The data for the Alpha-United, Inc. HHT design showed that the heat exchanger meet the requirement while operating in PI. There is data to indicate that the heat exchanger will vaporize the THI oxygen flowrate with hydrogen flowrates much higher or lower than design point. The HHT design also maintained the oxidizer side flow stability, but exceeded pressure loss requirements on both sides in the PI mode.

Ken Maynard
Ken Maynard
RL10 Systems Performance

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TABLE 1

OXIDIZER HEAT EXCHANGER TEST
ALPHA UNITED INC.
HIGH HEAT TRANSFER DESIGN

PUMPED IDLE MODE

TEST POINT	93	94	95	96	97	98	99	100
H2 HEX INLET TEMP - DEG R	632.459	632.798	633.690	634.412	635.450	635.220	635.346	627.618
H2 HEX INLET PRESSURE - PSI	42.249	42.273	40.789	38.815	38.434	33.719	30.779	37.240
H2 HEX INTERSTAGE TEMP - DEG R	606.420	601.425	588.881	573.829	533.444	446.406	434.231	444.067
H2 HEX INTERSTAGE PRESS - PSI	39.496	39.509	38.137	36.301	35.946	31.504	28.688	34.859
H2 HEX DISCH TEMP - DEG R	567.119	558.080	537.637	513.259	461.666	294.584	233.940	348.106
H2 HEX DISCH PRESSURE - PSI	36.741	36.742	35.485	33.804	33.453	29.291	26.606	32.508
H2 MEASURED FLOWRATE - LBM/SEC	0.197	0.199	0.194	0.187	0.194	0.197	0.194	0.206
H2 CALCULATED FLOWRATE - LBM/SEC	0.197	0.199	0.194	0.187	0.194	0.197	0.194	0.206
H2 HEX PRESSURE LOSS - PSI	5.506	5.528	5.304	5.028	4.976	4.430	4.182	4.762
H2 HEX TEMPERATURE DROP - DEG R	65.340	74.718	96.053	121.153	173.784	340.636	401.406	279.512
O2 HEX INLET TEMP - DEG R	174.335	174.680	174.213	173.748	178.748	171.832	168.806	171.361
O2 HEX INLET PRESSURE - PSI	90.336	89.013	90.286	89.213	88.929	87.744	85.098	87.444
O2 HEX DISCH TEMP - DEG R	381.014	362.183	274.020	232.294	201.889	245.568	193.994	198.036
O2 HEX DISCH PRESSURE - PSI	90.069	88.836	89.961	88.238	85.070	79.080	69.090	79.024
O2 MEASURED FLOWRATE - LBM/SEC	2.182	2.185	2.199	2.545	2.248	2.626	3.702	2.595
O2 CALCULATED FLOWRATE - LBM/SEC	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
O2 PRESSURE LOSS - PSI	0.473	0.370	0.355	0.589	4.361	8.664	16.008	8.461
O2 TEMPERATURE RISE - DEG R	206.679	187.503	99.807	58.546	23.141	73.736	25.188	26.675
H2 SIDE ACD - SQ. IN	2.453	2.471	2.460	2.432	2.536	2.741	2.804	2.734
O2 SIDE ACD -SQ. IN	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
OVERALL H2 HEAT FLUX - BTU/SEC	45.270	52.222	65.635	79.904	119.589	246.262	287.619	209.631
INTERSTAGE H2 HEAT FLUX - BTU/SEC	17.996	21.863	30.498	39.741	69.587	132.303	138.966	134.997
LOX SIDE HEAT FLUX - BTU/SEC	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
O2 EXIT QUALITY	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
STABLE	NO	NO	NO	NO	NO	NO	NO	NO

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TABLE 1
(continued)

OXIDIZER HEAT EXCHANGER TEST
ALPHA UNITED INC.
HIGH HEAT TRANSFER DESIGN

PUMPED IDLE MODE

TEST POINT	101	102	103	104	105	106	107	108
H2 HEX INLET TEMP - DEG R	628.614	628.840	629.350	630.461	632.515	633.254	638.894	641.653
H2 HEX INLET PRESSURE - PSI	38.463	32.200	35.018	35.302	31.412	32.130	29.741	30.451
H2 HEX INTERSTAGE TEMP - DEG R	524.335	436.830	465.735	464.365	454.954	456.587	437.123	461.350
H2 HEX INTERSTAGE PRESS - PSI	35.955	29.892	32.572	32.870	29.120	29.729	27.557	28.179
H2 HEX DISCH TEMP - DEG R	447.496	233.752	335.273	333.164	242.780	245.077	227.105	244.302
H2 HEX DISCH PRESSURE - PSI	33.475	27.608	30.145	30.462	26.872	27.366	25.391	25.931
H2 MEASURED FLOWRATE - LBM/SEC	0.197	0.207	0.203	0.204	0.200	0.206	0.193	0.193
H2 CALCULATED FLOWRATE - LBM/SEC	0.196	0.207	0.203	0.204	0.200	0.206	0.193	0.193
H2 HEX PRESSURE LOSS - PSI	5.015	4.616	4.893	4.863	4.583	4.801	4.368	4.544
H2 HEX TEMPERATURE DROP - DEG R	181.118	395.088	294.077	297.297	389.735	388.177	411.789	397.351
O2 HEX INLET TEMP - DEG R	172.274	168.148	169.985	169.585	167.194	167.233	166.302	166.916
O2 HEX INLET PRESSURE - PSI	87.796	85.345	87.629	85.906	88.408	88.294	85.400	89.031
O2 HEX DISCH TEMP - DEG R	200.243	193.917	216.945	222.972	220.497	250.706	194.456	278.241
O2 HEX DISCH PRESSURE - PSI	83.618	68.987	79.731	78.030	78.944	79.582	70.387	81.541
O2 MEASURED FLOWRATE - LBM/SEC	1.905	3.495	1.986	2.506	2.595	2.464	3.573	2.225
O2 CALCULATED FLOWRATE - LBM/SEC	N/C	N/C	N/C	N/C	2.621	2.557	N/C	2.248
O2 PRESSURE LOSS - PSI	4.209	16.358	7.898	7.876	9.586	8.963	15.013	7.556
O2 TEMPERATURE RISE - DEG R	27.969	25.769	46.960	53.387	53.303	83.473	28.154	111.325
H2 SIDE ACD - SQ. IN	2.551	2.880	2.726	2.736	2.815	2.853	2.802	2.770
O2 SIDE ACD -SQ. IN	N/C	N/C	N/C	N/C	0.212	0.214	N/C	0.205
OVERALL H2 HEAT FLUX - BTU/SEC	126.688	302.533	217.486	220.865	288.023	295.296	293.513	283.367
INTERSTAGE H2 HEAT FLUX - BTU/SEC	72.202	141.685	117.920	120.224	126.131	129.168	138.643	123.540
LOX SIDE HEAT FLUX - BTU/SEC	N/C	N/C	N/C	N/C	261.750	274.022	N/C	255.528
O2 EXIT QUALITY	N/C	N/C	N/C	N/C	1.0	1.0	N/C	1.0
STABLE	NO	NO	NO	NO	YES	YES	NO	YES

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TABLE 1
(continued)

OXIDIZER HEAT EXCHANGER TEST
ALPHA UNITED INC.
HIGH HEAT TRANSFER DESIGN

TANK HEAD IDLE MODE

TEST POINT	111	112	115	116	117	118	119	120
H2 HEX INLET TEMP - DEG R	599.644	597.071	610.233	599.058	603.314	602.868	606.893	597.462
H2 HEX INLET PRESSURE - PSI	24.281	35.916	15.982	40.507	41.051	15.760	14.832	14.842
H2 HEX INTERSTAGE TEMP - DEG R	588.298	591.629	529.173	584.077	594.300	525.002	0.0	200.224
H2 HEX INTERSTAGE PRESS - PSI	22.939	33.403	15.769	37.561	38.053	15.582	0.0	14.823
H2 HEX DISCH TEMP - DEG R	565.668	579.465	421.483	562.043	578.774	428.799	193.965	188.783
H2 HEX DISCH PRESSURE - PSI	21.508	30.874	15.521	34.602	35.045	15.384	14.824	14.824
H2 MEASURED FLOWRATE - LBM/SEC	0.101	0.172	0.034	0.202	0.202	0.030	0.015	0.015
H2 CALCULATED FLOWRATE - LBM/SEC	0.102	0.172	0.034	0.201	0.202	0.031	0.015	0.015
H2 HEX PRESSURE LOSS - PSI	2.684	5.026	0.427	5.892	5.996	0.357	0.029	0.037
H2 HEX TEMPERATURE DROP - DEG R	33.976	17.606	188.750	37.015	24.540	174.069	412.928	408.679
O2 HEX INLET TEMP - DEG R	173.414	174.608	173.121	173.127	175.384	175.778	173.646	175.363
O2 HEX INLET PRESSURE - PSI	26.805	28.842	28.938	29.204	30.722	30.722	29.202	30.553
O2 HEX DISCH TEMP - DEG R	482.043	524.136	175.906	178.071	397.558	202.498	175.077	178.775
O2 HEX DISCH PRESSURE - PSI	26.444	28.335	28.191	28.478	30.197	30.038	28.245	29.757
O2 MEASURED FLOWRATE - LBM/SEC	0.305	0.312	0.318	0.307	0.207	0.206	0.301	0.222
O2 CALCULATED FLOWRATE - LBM/SEC	N/C	N/C	N/C	0.306	N/C	0.205	0.299	0.221
O2 PRESSURE LOSS - PSI	0.248	0.343	0.598	0.594	0.376	0.470	0.816	0.659
O2 TEMPERATURE RISE - DEG R	308.629	349.528	2.785	4.944	222.174	26.720	1.431	3.412
H2 SIDE ACD - SQ. IN	1.682	2.220	0.971	2.433	2.428	0.915	0.854	0.801
O2 SIDE ACD -SQ. IN	N/C	N/C	N/C	0.100	N/C	0.076	0.084	0.069
OVERALL H2 HEAT FLUX - BTU/SEC	12.164	10.655	22.946	26.255	17.417	19.122	23.028	22.912
INTERSTAGE H2 HEAT FLUX - BTU/SEC	4.056	3.294	9.699	10.610	6.393	8.433	0.0	22.327
LOX SIDE HEAT FLUX - BTU/SEC	N/C	N/C	N/C	27.449	N/C	19.307	26.578	19.642
O2 EXIT QUALITY	N/C	N/C	N/C	0.965	N/C	1.0	0.867	1.0
STABLE	NO	NO	NO	YES	NO	YES	YES	YES

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TABLE 2.

OXIDIZER HEAT EXCHANGER TEST
ALPHA UNITED INC.
HIGH HEAT TRANSFER DESIGN

DESIGN POINTS FOR PUMPED IDLE AND TANK HEAD IDLE

TEST POINT	105	116	119
OPERATONAL MODE	PI	THI	THI
H2 HEX INLET TEMP - DEG R	632.515 (659)	599.058 (594)	606.893
H2 HEX INLET PRESSURE - PSI	31.412 (46.7)	40.507 (9.0)	14.832
H2 HEX INTERSTAGE TEMP - DEG R	454.954	584.077	0.0
H2 HEX INTERSTAGE PRESS - PSI	29.120	37.561	0.0
H2 HEX DISCH TEMP - DEG R	242.780	562.043	193.965
H2 HEX DISCH PRESSURE - PSI	26.872	34.602	14.824
H2 MEASURED FLOWRATE - LBM/SEC	0.200	0.202	0.015
H2 CALCULATED FLOWRATE - LBM/SEC	0.200 (0.190)	0.201 (0.094)	0.015
H2 HEX PRESSURE LOSS - PSI	4.583 (2.4 max)	5.892 (2.1 max)	0.029
H2 HEX TEMPERATURE DROP - DEG R	389.735	37.015	412.928
O2 HEX INLET TEMP - DEG R	167.194 (168)	173.127 (165.8)	173.646
O2 HEX INLET PRESSURE - PSI	88.408 (110)	29.204 (20)	29.202
O2 HEX DISCH TEMP - DEG R	220.497	178.071	175.077
O2 HEX DISCH PRESSURE - PSI	78.944	28.478	28.245
O2 MEASURED FLOWRATE - LBM/SEC	2.595	0.307	0.301
O2 CALCULATED FLOWRATE - LBM/SEC	2.621 (2.84)	0.306 (0.31)	0.299
O2 PRESSURE LOSS - PSI	9.586 (4.7 max)	0.594 (2.3 max)	0.816
O2 TEMPERATURE RISE - DEG R	53.303	4.944	1.431
H2 SIDE ACD - SQ. IN	2.815	2.433	0.854
O2 SIDE ACD -SQ. IN	0.212	0.100	0.084
OVERALL H2 HEAT FLUX - BTU/SEC	288.023	26.255	23.028
INTERSTAGE H2 HEAT FLUX - BTU/SEC	126.131	10.610	0.0
LOX SIDE HEAT FLUX - BTU/SEC	261.750	27.449	26.578
O2 EXIT QUALITY	1.000	0.965	0.867

NOTE: Specification requirements in parenthesis

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TABLE 3.

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

TANK HEAD IDLE MODE

TEST POINT	130	131	132	133	134	135	136	137
H2 HEX INLET TEMP - DEG R	604.004	601.479	600.304	600.932	599.280	604.284	601.914	598.932
H2 HEX INLET PRESSURE - PSI	15.525	17.903	21.173	23.292	20.976	21.299	20.974	20.095
H2 HEX DISCH TEMP - DEG R	239.175	420.008	493.696	504.178	489.966	527.632	500.850	411.492
H2 HEX DISCH PRESSURE - PSI	15.301	17.152	19.909	21.747	19.759	20.073	19.767	18.979
H2 MEASURED FLOWRATE - LBM/SEC	0.042	0.074	0.099	0.121	0.097	0.101	0.096	0.100
H2 CALCULATED FLOWRATE - LBM/SEC	0.041	0.074	0.103	0.121	0.101	0.101	0.100	0.100
H2 HEX PRESSURE LOSS - PSI	0.190	0.676	1.171	1.459	1.131	0.597	1.130	1.048
H2 HEX TEMPERATURE DROP - DEG R	364.829	181.471	106.608	96.754	109.314	76.652	101.064	187.440
O2 HEX INLET TEMP - DEG R	175.449	176.596	174.677	175.621	174.263	174.929	175.786	173.446
O2 HEX INLET PRESSURE - PSI	31.014	31.308	29.926	31.279	29.223	30.224	31.406	28.120
O2 HEX DISCH TEMP - DEG R	578.349	600.167	601.894	600.808	600.100	602.120	602.893	596.849
O2 HEX DISCH PRESSURE - PSI	30.247	30.424	29.099	30.365	28.354	29.654	30.596	26.604
O2 MEASURED FLOWRATE - LBM/SEC	0.277	0.220	0.267	0.283	0.284	0.210	0.251	0.414
O2 CALCULATED FLOWRATE - LBM/SEC	0.276	0.218	0.264	0.281	0.282	0.208	0.249	0.416
O2 CALCULATED FLOWRATE - LBM/SEC	0.276	0.218	N/C	N/C	N/C	N/C	N/C	N/C
O2 PRESSURE LOSS - PSI	0.833	0.881	0.843	0.900	0.820	1.157	0.785	1.514
O2 TEMPERATURE RISE - DEG R	401.900	423.571	426.217	424.187	424.837	426.191	426.107	422.403
H2 SIDE ACD - SQ. IN	1.425	1.819	2.137	2.324	2.109	2.459	2.099	2.145
O2 SIDE ACD -SQ. IN	0.077	0.059	N/C	N/C	N/C	N/C	N/C	N/C
OVERALL H2 HEAT FLUX - BTU/SEC	55.189	47.966	38.977	41.444	39.073	27.280	35.807	67.106
LOX SIDE HEAT FLUX - BTU/SEC	48.936	39.636	N/C	N/C	N/C	N/C	N/C	N/C
O2 EXIT QUALITY	1.0	1.0	N/C	N/C	N/C	N/C	N/C	N/C
STABLE	YES	YES	NO	NO	NO	NO	NO	NO

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TABLE 3
(continued)

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

TANK HEAD IDLE MODE

TEST POINT	138	139
H2 HEX INLET TEMP - DEG R	607.732	601.711
H2 HEX INLET PRESSURE - PSI	19.184	20.868
H2 HEX DISCH TEMP - DEG R	315.514	474.368
H2 HEX DISCH PRESSURE - PSI	18.151	19.635
H2 MEASURED FLOWRATE - LBM/SEC	0.100	0.098
H2 CALCULATED FLOWRATE - LBM/SEC	0.100	0.102
H2 HEX PRESSURE LOSS - PSI	0.951	1.149
H2 HEX TEMPERATURE DROP - DEG R	292.218	127.343
O2 HEX INLET TEMP - DEG R	172.120	176.132
O2 HEX INLET PRESSURE - PSI	27.748	33.051
O2 HEX DISCH TEMP - DEG R	581.285	602.295
O2 HEX DISCH PRESSURE - PSI	25.234	31.996
O2 MEASURED FLOWRATE - LBM/SEC	0.515	0.305
O2 CALCULATED FLOWRATE - LBM/SEC	0.514	N/C
O2 PRESSURE LOSS - PSI	2.468	0.984
O2 TEMPERATURE RISE - DEG R	409.165	426.163
H2 SIDE ACD - SQ. IN	2.248	2.139
O2 SIDE ACD -SQ. IN	0.083	N/C
OVERALL H2 HEAT FLUX - BTU/SEC	107.239	46.286
LOX SIDE HEAT FLUX - BTU/SEC	92.269	N/C
O2 EXIT QUALITY	1.0	N/C
STABLE	YES	NO

TABLE 3
(continued)

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

PUMPED IDLE MODE

TEST POINT	140	141	143	144	145	146	147	148
H2 HEX INLET TEMP - DEG R	634.052	634.749	637.057	637.805	639.407	638.797	638.555	637.938
H2 HEX INLET PRESSURE - PSI	38.229	36.316	36.187	36.390	35.234	34.871	32.486	27.673
H2 HEX DISCH TEMP - DEG R	632.940	612.679	587.463	570.603	551.568	515.501	436.242	280.891
H2 HEX DISCH PRESSURE - PSI	35.346	33.501	33.359	33.477	32.410	32.039	29.861	25.524
H2 MEASURED FLOWRATE - LBM/SEC	0.193	0.188	0.190	0.195	0.191	0.195	0.192	0.189
H2 CALCULATED FLOWRATE - LBM/SEC	0.193	0.188	0.190	0.195	0.191	0.195	0.192	0.189
H2 HEX PRESSURE LOSS - PSI	2.802	2.743	2.764	2.831	2.765	2.788	2.591	2.105
H2 HEX TEMPERATURE DROP - DEG R	1.112	22.070	49.594	67.202	87.839	123.296	202.313	357.047
O2 HEX INLET TEMP - DEG R	171.397	171.581	165.268	165.040	165.000	165.260	165.691	174.686
O2 HEX INLET PRESSURE - PSI	87.730	90.837	90.243	90.034	88.192	88.928	87.823	82.620
O2 HEX DISCH TEMP - DEG R	540.603	631.907	636.059	638.050	639.609	636.466	612.331	411.087
O2 HEX DISCH PRESSURE - PSI	88.029	90.731	90.048	89.842	87.666	88.059	84.962	77.251
O2 MEASURED FLOWRATE - LBM/SEC	1.009	0.230	1.605	1.596	1.910	2.178	2.368	3.018
O2 CALCULATED FLOWRATE - LBM/SEC	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
O2 PRESSURE LOSS - PSI	0.049	0.365	0.460	0.410	0.801	1.125	2.987	5.470
O2 TEMPERATURE RISE - DEG R	369.206	460.326	470.791	473.010	474.609	471.206	446.640	236.401
H2 SIDE ACD - SQ. IN	2.859	2.849	2.882	2.937	2.923	2.987	3.038	3.284
O2 SIDE ACD -SQ. IN	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
OVERALL H2 HEAT FLUX - BTU/SEC	0.758	14.538	33.054	45.980	58.983	84.833	138.126	248.499
LOX SIDE HEAT FLUX - BTU/SEC	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
O2 EXIT QUALITY	N/C	N/C	N/C	N/C	N/C	N/C	N/C	N/C
STABLE	NO	NO	NO	NO	NO	NO	NO	NO

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TABLE 3
(continued)

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

PUMPED IDLE MODE

TEST POINT	149	150	151	152	153	154	155	156
H2 HEX INLET TEMP - DEG R	638.010	637.824	652.313	658.466	638.351	633.386	557.247	635.459
H2 HEX INLET PRESSURE - PSI	24.625	25.861	21.128	18.057	25.396	28.211	25.672	25.321
H2 HEX DISCH TEMP - DEG R	217.057	229.920	203.630	189.313	227.770	257.974	215.627	230.666
H2 HEX DISCH PRESSURE - PSI	23.028	24.024	20.022	17.432	23.631	25.997	23.934	23.563
H2 MEASURED FLOWRATE - LBM/SEC	0.184	0.194	0.146	0.104	0.190	0.208	0.199	0.186
H2 CALCULATED FLOWRATE - LBM/SEC	0.184	0.194	0.146	0.104	0.190	0.208	0.199	0.186
H2 HEX PRESSURE LOSS - PSI	1.561	1.781	1.090	0.603	1.730	2.157	1.685	1.692
H2 HEX TEMPERATURE DROP - DEG R	420.953	407.904	448.683	469.153	410.581	375.412	341.620	404.793
O2 HEX INLET TEMP - DEG R	165.958	166.583	166.517	166.539	166.321	166.774	166.508	169.158
O2 HEX INLET PRESSURE - PSI	82.824	87.137	85.005	86.322	86.104	87.884	86.771	90.482
O2 HEX DISCH TEMP - DEG R	195.647	199.631	197.873	199.157	197.684	276.857	198.992	204.097
O2 HEX DISCH PRESSURE - PSI	71.855	80.438	78.059	81.761	78.309	82.059	81.248	84.497
O2 MEASURED FLOWRATE - LBM/SEC	3.874	2.537	3.291	2.869	2.928	2.287	2.696	2.573
O2 CALCULATED FLOWRATE - LBM/SEC	N/C	2.554	N/C	N/C	N/C	2.295	2.702	2.574
O2 PRESSURE LOSS - PSI	11.414	6.969	7.270	4.758	8.196	6.099	5.757	6.401
O2 TEMPERATURE RISE - DEG R	29.689	33.048	31.356	32.618	31.363	110.083	32.484	34.939
H2 SIDE ACD - SQ. IN	3.524	3.569	3.201	2.761	3.534	3.556	3.466	3.462
O2 SIDE ACD -SQ. IN	N/C	0.242	N/C	N/C	N/C	0.233	0.281	0.255
OVERALL H2 HEAT FLUX - BTU/SEC	285.576	292.888	240.637	179.451	288.422	288.139	253.932	277.713
LOX SIDE HEAT FLUX - BTU/SEC	N/C	241.771	N/C	N/C	N/C	260.185	255.315	243.431
O2 EXIT QUALITY	N/C	1.0	N/C	N/C	N/C	1.0	0.994	1.0
STABLE	NO	YES	NO	NO	NO	YES	YES	YES

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TABLE 3
(continued)

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

PUMPED IDLE MODE

TEST POINT	157	158	159	160	161
H2 HEX INLET TEMP - DEG R	627.640	647.310	662.314	642.180	642.180
H2 HEX INLET PRESSURE - PSI	29.553	21.572	18.254	25.566	25.566
H2 HEX DISCH TEMP - DEG R	254.702	208.513	191.918	231.124	231.124
H2 HEX DISCH PRESSURE - PSI	27.227	20.376	17.578	23.725	23.725
H2 MEASURED FLOWRATE - LBM/SEC	0.222	0.149	0.106	0.190	0.195
H2 CALCULATED FLOWRATE - LBM/SEC	0.222	0.149	0.106	0.190	0.190
H2 HEX PRESSURE LOSS - PSI	2.268	1.153	0.634	1.774	1.774
H2 HEX TEMPERATURE DROP - DEG R	372.938	438.797	470.396	411.056	411.056
02 HEX INLET TEMP - DEG R	168.434	168.480	168.044	167.860	167.860
02 HEX INLET PRESSURE - PSI	90.358	89.953	89.679	89.733	89.733
02 HEX DISCH TEMP - DEG R	209.736	200.030	200.204	199.084	199.084
02 HEX DISCH PRESSURE - PSI	83.291	84.664	85.291	82.511	82.511
02 MEASURED FLOWRATE - LBM/SEC	2.664	2.773	2.845	2.800	2.844
02 CALCULATED FLOWRATE - LBM/SEC	2.667	2.730	2.845	2.806	2.806
02 CALCULATED FLOWRATE - LBM/SEC	2.667	N/C	N/C	N/C	N/C
02 PRESSURE LOSS - PSI	7.452	5.727	4.729	7.564	7.564
02 TEMPERATURE RISE - DEG R	41.302	31.550	32.160	31.224	31.224
H2 SIDE ACD - SQ. IN	3.686	3.195	2.770	3.511	3.511
02 SIDE ACD -SQ. IN	0.245	0.285	0.325	0.255	0.255
02 SIDE ACD -SQ. IN	0.245	N/C	N/C	N/C	N/C
OVERALL H2 HEAT FLUX - BTU/SEC	305.653	240.532	182.725	288.112	288.112
LOX SIDE HEAT FLUX - BTU/SEC	257.178	N/C	N/C	N/C	N/C
02 EXIT QUALITY	1.0	N/C	N/C	N/C	N/C
STABLE	YES	NO	NO	NO	NO

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TABLE 4

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

DESIGN POINTS FOR PUMPED IDLE AND TANK HEAD IDLE

TEST POINT	138	156
OPERATIONAL MODE	THI	PI
H2 HEX INLET TEMP - DEG R	607.732 (594)	635.459 (659)
H2 HEX INLET PRESSURE - PSI	19.184 (9.0)	25.321 (46.7)
H2 HEX DISCH TEMP - DEG R	315.514	230.666
H2 HEX DISCH PRESSURE - PSI	18.151	23.563
H2 MEASURED FLOWRATE - LBM/SEC	0.100	0.186
H2 CALCULATED FLOWRATE - LBM/SEC	0.100 (0.094)	0.186 (0.19)
H2 HEX PRESSURE LOSS - PSI	0.951 (2.1 max)	1.692 (2.4 max)
H2 HEX TEMPERATURE DROP - DEG R	292.218	404.793
O2 HEX INLET TEMP - DEG R	172.120 (165.8)	169.158 (168)
O2 HEX INLET PRESSURE - PSI	27.748 (20)	90.482 (110)
O2 HEX DISCH TEMP - DEG R	581.285	204.097
O2 HEX DISCH PRESSURE - PSI	25.234	84.497
O2 MEASURED FLOWRATE - LBM/SEC	0.515	2.573
O2 CALCULATED FLOWRATE - LBM/SEC	0.514 (0.31)	2.574 (2.84)
O2 PRESSURE LOSS - PSI	2.468 (2.3 max)	6.401 (4.7 max)
O2 TEMPERATURE RISE - DEG R	409.165	34.939
H2 SIDE ACD - SQ. IN	2.248	3.462
O2 SIDE ACD -SQ. IN	0.083	0.255
OVERALL H2 HEAT FLUX - BTU/SEC	107.239	277.713
LOX SIDE HEAT FLUX - BTU/SEC	92.269	243.431
O2 EXIT QUALITY	1.000	1.000

TABLE 5

OXIDIZER HEAT EXCHANGER TEST
ALPHA UNITED INC.
HIGH HEAT TRANSFER DESIGN

TEST POINT	OXIDIZER DISCHARGE PRESSURE OSCILLATION (+/-) psi
93	22.0
94	22.6
95	23.2
96	21.5
97	18.1
98	0.9
99	0.9
100	12.8
101	0.9
102	0.9
103	20.6
104	18.7
105	2.4
106	10.6
111 thru 120	STEADY

TABLE 6

OXIDIZER HEAT EXCHANGER TEST
UNITED AIRCRAFT PRODUCTS INC.
LOW HEAT TRANSFER DESIGN

TEST POINT	OXIDIZER DISCHARGE PRESSURE OSCILLATION (+/-) psi
130 thru 139	STEADY
140	7.3
141	0.2
142	13.5
143	17.9
144	18.6
145	17.7
146	21.6
147	26.6
148	19.7
149 thru 161	STEADY

APPPENDIX B

PRATT & WHITNEY
Government Products Division

INTERNAL CORRESPONDENCE

To: D.E. Galler
From: Raymond B. Kaldor
Subject: Oxidizer Heat Exchanger Test Analysis of Second Units
Date: March 5, 1987
Copy To: J.R. Brown, R.R. Foust, P.G. Kanic, T.D. Kmiec, C.D. Limerick, R.J. Peckham, W.C. Ring, R.H. Wright, File

Reference:
1. Oxidizer Heat Exchanger Performance Test Plan, February 27 1986, by P.G. Kanic
2. Oxidizer Heat Exchanger Performance Test Plan, November 7 1986, by Ken Maynard
3. Low Heat Transfer Oxidizer Heat Exchanger Design and Analysis Report, January 30 1987, FR-19135-2
4. High Heat Transfer Oxidizer Heat Exchanger Design and Analysis, January 30 1987, FR-19289-1

HIGHLIGHTS

- The United Aircraft Products (UAP) low heat transfer rate unit 2 heat exchanger gasified liquid oxygen to above .95 quality consistently. The unit 2 Alpha United (AU) high heat transfer rate heat exchanger did not consistently gasify the liquid oxygen above .95 quality at pumped idle (PI). At tank head idle (THI) while inverted, unit 2 of each design completely vaporized the oxygen.

- PI pressure loss of both the oxygen and hydrogen flows for both the UAP and AU models is projected to exceed the maximums of references 3 and 4. THI pressure loss of both the oxygen and hydrogen flows for both the UAP and AU models will be under the maximums of references 3 and 4.

- Oxygen flow oscillation was not consistently under the maximum of references 3 & 4 for either model in PI simulation. Oxygen flow oscillation was consistently under the maximum of references 3 & 4 for the AU model in THI simulation while inverted. Oxygen flow for the inverted UAP unit at THI was not stable enough to measure.

Raymond B. Kaldor

Raymond B. Kaldor, Ext. 4805
Systems Performance

6308C

BACKGROUND

A heat exchanger will be used in the RL10-IIB multi-mode low thrust engine. Heat from the hydrogen which has passed through the jacket will be used to gasify liquid oxygen. During low thrust engine operation with the heat exchanger, PI and THI, gaseous oxygen instead of liquid oxygen would be provided to the injector, and the pressure drop across the injector would be increased. The increased pressure loss would provide for stable combustion. Without the heat exchanger, the small pressure drop across the injector could allow oxygen flow to be cut off by instability in chamber pressure. In full thrust operation, the heat exchanger would be used to pressurize the liquid oxygen tank with gaseous oxygen.

A primary concern of this type of heat exchanger is large oxygen flow oscillation induced by nucleate boiling of the liquid oxygen within the heat exchanger. Two heat exchanger designs were developed with this consideration, a low heat transfer rate model by United Aircraft Products and a high heat transfer rate model with volume damping by Alpha United.

This report details the testing results of the second unit from each vendor, compares unit 2 and unit 1 results for performance repeatability of each design, and compares the performance of the different designs.

DISCUSSION

The test stand could not provide oxygen or hydrogen inlet pressures as low as specified for THI operation, nor could the stand provide oxygen or hydrogen pressures as high as specified for PI operation. Extrapolations have been made where appropriate.

Oxygen flow oscillation references in this paper, for references 3 & 4 and for test results, are differences from minimum to maximum flow rate.

The heat exchangers provided by United Aircraft Products, a low heat transfer rate heat exchanger, and Alpha United, a high heat transfer rate heat exchanger, 2 units each, did not meet all criteria of references 3 and 4.

Both units of the UAP heat exchanger adequately gasified the oxygen, but unit 2 of the AU model did not consistently gasify to a quality of .95. Because of problems measuring oxygen flow rate, the quality of the AU unit 2 oxygen discharge may be different from calculated, but still less than 1.

The second units of each model were inverted in an attempt to quantify the effects of zero gravity (g). The oxygen flow could not be determined for the UAP unit as there were pressure drop reversals across the lox flow measuring orifice, so direct determination of oxygen heat gain, oxygen flow rate and oscillation could not be made. The AU unit did give some tests with measurable flow and the performance is reflected in table 1 and figures with an A suffix. The oxygen flow measuring orifice used during the second unit AU THI testing in the inverted position was larger than the orifice used for all other THI testing. This could be the reason why there was measurable flow during the inverted AU testing and there was not measurable flow during inverted UAP testing. Inverting the heat exchangers tested a negative g application, not a zero g application.

Table 1 shows the results of the second unit tests in pumped idle mode in the upright position, and tank head idle mode in the inverted (negative g) position. The values are averages over a 5 second test period. When there were pressure reversals across the oxygen flow measuring orifice, oxygen flow rate and oscillation could not be directly determined. Some of these test points are shown with minimum values for oxygen flow rate oscillation, and are noted by the > symbol.

Six test points were analyzed scan by scan. One stable test point for each unit of both models at pumped idle (PI) and for unit 1 of both models at tank head idle (THI) in an upright position was chosen. The scan segment chosen for each point includes the 5 second test at the end of the segment. Of the 31 scans analyzed (arbitrarily timed from 0. to 15. seconds, inclusive) the last 10 scans (10.5 to 15. seconds inclusive) represent the 5 seconds used for averages. The scan by scan analysis shows that the oxygen is not undergoing a smooth and steady phase change. During analysis, a test was considered "stable" if there were no pressure drop reversals across the liquid oxygen flow measuring orifice.

Table 2 shows the comparison of averages over 15. seconds for the above test points selected for scan by scan analysis. The specifications listed are from references 3 & 4. These points are used in figures 7 through 19.

Table 3 shows repeatability from unit to unit for both models in PI operation. Units 2 of both models were not tested in THI operation in an upright position, and units 1 of both models were not tested in THI operation in an inverted position. Compared to unit 1, unit 2 of the AU model delivered less hydrogen pressure loss, a wider range of oxygen pressure loss, about the same oxygen flow oscillation, and questionable oxygen discharge quality. The unit 2 UAP model, when compared to unit 1, delivered less hydrogen pressure loss, a wider range of oxygen pressure loss, less oxygen flow oscillation and the same acceptable oxygen discharge quality.

Figure 1 summarizes the testing of the second units of heat exchangers from both UAP and AU. It should be noted that the stand could not provide pressures as low as specified for THI nor could it provide pressures as high as specified for PI. Both models were tested in an upright position to simulate PI operation and in an inverted position to simulate THI operation. The UAP model met the quality specification for PI operation but the AU model did not. There was no published criteria for quality in THI operation, however both designs completely vaporized the oxygen at THI. The UAP was in compliance for hydrogen pressure loss both in PI and inverted THI operation at the pressures tested, but the AU was not consistently in compliance. The UAP was within or close to compliance with oxygen flow oscillation criteria at PI simulation, but the AU was not consistently in compliancy under similar conditions. The UAP had pressure reversals across the flow measuring orifice for every test in the inverted position at THI, so no oxygen flow or oscillation data is available. The AU model had measurable flow at THI while inverted but the oxygen flow oscillation exceeded the THI specification. Both the AU and the UAP models exceeded oxygen pressure loss specified for PI, while being tested at pressures that were less than specified for PI operation. Both models had less oxygen pressure loss than specified for THI while inverted.

Figure 2 reflects repeatability, conformance to oscillation criteria and a connection at pumped idle between oxygen flow rate, oxygen/hydrogen flow ratio, and oxygen flow oscillation. As oxygen flow rate and flow ratio are increased, oscillation falls. The higher the flow ratio, the lower the rate at which heat is added per pound mass of oxygen, and the gentler the boiling.

Figures 3 & 3A reflect THI conformance to oscillation criteria of references 3 & 4. Figure 3 shows oscillation, oxygen flow rate, and flow ratio of unit 1 of each model in the upright position. Figure 3A shows the same information for unit 2 of the AU model in the inverted position. The flow (and therefore the flow oscillation) of the unit 2 UAP heat exchanger could not be determined because of pressure drop reversals across the oxygen flow measuring orifice. There is no obvious relationship in THI operation between oxygen flow rate, flow ratio and oscillation as there is at PI. As mentioned previously, the oxygen flow measuring orifice used during inverted AU THI testing was larger than the oxygen orifice used for all other THI testing.

Figure 4 displays oxygen flow oscillation noted for oxygen inlet pressures tested. The stand was not capable of providing inlet pressures as low as specified for THI or as high as specified for PI. The wide range of oscillation exhibited at PI inlet pressures suggests that inlet pressure has little to do with oxygen flow oscillation. Figure 4A shows the same information for the unit 2 AU heat exchanger in an inverted position at THI.

Figure 5 shows repeatability and conformance to hydrogen pressure loss criteria for both units of both models at PI, and for unit 1 of both models at THI. The design requirements for hydrogen inlet pressure and hydrogen pressure loss are marked on the figure. Units 1 and 2 of the UAP model were tested over similar hydrogen inlet pressures in pumped idle mode with good repeatability. Unit 2 of the AU model was tested over different hydrogen inlet pressures than unit 1, with appropriate hydrogen pressure drops noted. For both models, pressure drop across the hydrogen side is approximated by a linear relationship to hydrogen heat exchanger inlet pressure. If the relationship of hydrogen pressure loss to hydrogen inlet pressure is extrapolated, neither the UAP nor the AU model will perform to specification in PI operation, though the UAP model is better than the AU. In THI operation, both models would give hydrogen pressure losses under the maximum specified.

Figure 5A shows THI pressure loss of the AU model in an inverted position. The hydrogen pressure loss to inlet pressure is the same as for the unit 1 AU model at THI in an upright position.

Figure 6 shows repeatability and conformance to oxygen pressure loss criteria. The design requirements for oxygen inlet pressure and pressure loss are marked on the figure for THI and PI. There is a range of pressure loss for each model in PI operation. At specified THI pressure, expected performance is better than criteria but at specified PI pressure, expected performance is worse than criteria. Figure 6A shows similar information for unit 2 of the AU model at THI in an inverted position. Oxygen pressure loss criteria is met.

Six test points were analyzed scan by scan for 15 seconds as mentioned previously. Analysis results for these six test points are shown graphically in figures 6 through 19. There is one symbol for every half second.

Figure 7 shows the change of hydrogen flow rate with a change in hydrogen inlet pressure. The variation within each test was small and predictable.

Figure 8 shows the scatter of oxygen flow rate against oxygen inlet pressure. The dynamics of phase change prevent the same close correlation of flow rate with pressure as noted with the single phase hydrogen flows, resulting in scatter of the data at PI. The scatter for the UAP model is less than that of the AU model.

Figure 9 shows oxygen pressure loss across the heat exchanger for inlet pressures tested. The bulk of the data shows that pressure drop of both the AU and the UAP heat exchangers would be greater than specified in references 3 & 4 for PI. The phase change affects pressure loss the same way it affects flow, causing scatter. The scatter for the UAP model is less than that of the AU model.

Figure 10 shows hydrogen pressure loss against hydrogen inlet pressure. Hydrogen pressure loss for an increase in inlet pressure shows the same small predictable variation that was noted for hydrogen flow.

APPENDIX

ANOMALIES

The calculated heat loss from the hydrogen was not matched by the calculated heat gain in the oxygen. The greatest error is thought to be in the oxygen flow rate calculation because of fluctuating pressure differences across the orifice. Even the most stable test points exhibited some orifice pressure oscillation, and a flow measuring orifice is intended to be used for steady flow. The oxygen is not simmering to a gaseous state, but is boiling in spurts, causing pressure changes inside the heat exchanger. Oxygen orifice pressure drop is used in the oxygen flow rate calculation, which in turn is used to calculate oxygen heat gain or discharge quality. If flow rate is being under estimated because of orifice pressure drop oscillation, then the heat gain is being underestimated and the discharge quality is being over estimated. The estimated steady state uncertainties in flow rate calculation is ±4% for oxygen and ±5% for hydrogen.

The flow rate measuring orifice geometric areas used in testing were as follows:

Hydrogen	1.539 sq. in.
Oxygen, PI	0.374 " "
Oxygen, THI, unit 2 AU inverted	0.108 " "
Oxygen, all other THI	0.048 " "

A larger oxygen flow orifice was used for the inverted THI testing of the second unit AU heat exchanger in an attempt to reduce flow oscillation. The flow of the inverted AU heat exchanger was more stable than the flow of the inverted UAP heat exchanger with the smaller orifice, so the performance of the two models is not comparable.

The hydrogen and oxygen flow measuring orifices are small compared to normal engine plumbing, and this magnifies back pressure problems due to phase change, which in turn affects flow rate calculations.

Figures 11 through 16 show the change of measured parameters with time for the 6 selected test points considered representative of their test series. There is one scan every half second, and the last 10 scans for these 6 tests reflect the time period over which the 5 second average values were obtained. This scan rate does not allow a trace of data that exactly represents the maximum and minimum values of the measured parameters. Therefore oxygen flow oscillation across the heat exchanger is greater than indicated.

The figures 17 through 19 show how a small change in oxygen pressure upstream of the orifice affected the test of point 16. This test is for the UAP second unit at PI.

Figure 17 shows oxygen orifice inlet pressure, oxygen orifice exit pressure, and oxygen orifice pressure drop. At 8.5 seconds, the orifice inlet pressure and the pressure drop dip slightly, then recover. This pressure dip is not shown for the orifice exit, indicating the origin of the pressure dip is upstream of the orifice and has nothing to do with the heat exchanger.

Figure 18 shows the effect this dip had on the oxygen flow and heat gain calculations. The oxygen flow is in oscillation at 10.5 seconds, where the 10 scans for average calculations begin. The average calculated value of the flow is less than it was prior to the pressure dip.

Figure 19 shows the heat rate gain and loss of the oxygen (QO) and hydrogen (QH). Prior to the pressure dip at 8.5 seconds, QO and QH were steady and not to far apart with QO greater than QH. The difference could be explained by the flow measurement error of either orifice. After the pressure dip, QH shows and increase and QO shows a decrease to a value less than QH.

The minor pressure dip in the supply line greatly affected the flow and heat transfer calculations. The heat exchanger is acting as a heat "bank" until flows stabilize, since QH shows an abrupt increase 1 scan after the oxygen pressure dip. In the last 3 seconds shown, QH is decreasing and QO is increasing, presumably toward their previous levels when flow was more stable. Also possible is an under estimation of oxygen flow rate in response to the oscillating orifice pressure drop.

The conclusion from figures 11 through 19 is that the testing was not steady state and the orifices introduced conditions that will not be present in flight.

METHODS

Flow rate was determined with calibrated orifices that were accurate to ±4% for liquid oxygen and ±5% for gaseous hydrogen. The oxygen flow was not steady state, and greater error than stated is suspected for oxygen flow rate. Heat gain or loss is calculated by multiplying mass flow rate by enthalpy change across the heat exchanger. If the oxygen discharge temperature is less than the saturated vapor temperature for the measured discharge pressure, then quality is calculated. The heat gained by the oxygen is assumed to be .85 times the heat lost from the hydrogen. This assumption is made to keep the quality calculations consistent with the heat transfer calculations, where QO averaged .85 times QH. In reality, the heat gained by the oxygen should be the same as the heat lost from the hydrogen, but the source of the measurement errors are not all on the oxygen side. Assuming QO to be equal to QH would bias any comparison of test points having quality calculations with test points having heat transfer calculations. The heat gained by the oxygen is divided by the mass flow rate of the oxygen to give the change in enthalpy of oxygen. This change in enthalpy is added to the inlet enthalpy of oxygen to give discharge enthalpy. The oxygen inlet and discharge pressures are used to give saturated liquid and vapor enthalpies. Quality is directly calculated from the enthalpies.

HYDROGEN / OXYGEN HEAT EXCHANGER SECOND UNIT TEST DATA

UNITED AIRCRAFT PRODUCTS, PUMPED IDLE, UPRIGHT POSITION

		PT 8	PT 9	PT 10	PT 11	PT 12	PT 13	PT 14	PT 15	PT 16
H2 HEX INLET TEMP - DEGR	=	636.974	636.535	635.973	635.404	647.859	653.168	642.675	635.746	638.132
H2 HEX INLET PRESSURE - PSI	=	29.320	26.289	24.211	24.349	20.905	17.574	23.177	25.754	23.811
H2 HEX DISCH TEMP - DEGR	=	395.985	271.489	219.783	223.785	207.839	187.344	219.703	236.829	221.624
H2 HEX DISCH PRESSURE - PSI	=	27.350	24.594	22.837	22.907	19.890	17.072	21.812	24.007	22.341
H2 FLOWRATE - LBM/SEC	=	0.173	0.178	0.176	0.177	0.142	0.097	0.169	0.192	0.175
H2 HEX INLET ENTH - BTU/LBM	=	2146.577	2144.987	2142.986	2141.001	2184.427	2202.888	2166.374	2142.222	2150.521
H2 HEX DISCH ENTH - BTU/LBM	=	1281.442	800.146	605.241	619.757	562.816	493.235	604.981	667.860	611.917
H2 HEX PRESSURE LOSS - PSI	=	2.160	1.845	1.501	1.543	1.081	0.540	1.450	1.835	1.557
H2 HEX TEMP DROP - DEGR	=	240.989	365.046	416.190	411.619	440.020	465.824	422.972	398.917	416.508
O2 HEX INLET TEMP - DEGR	=	176.864	169.352	165.685	165.883	166.047	166.652	166.906	167.114	166.944
O2 HEX INLET PHASE	=	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
O2 HEX INLET SAT TEMP - DEGR	=	199.832	199.470	199.315	199.664	200.451	200.222	200.380	200.808	202.123
O2 HEX INLET PRESSURE - PSI	=	84.487	83.343	82.857	83.954	86.469	85.734	86.242	87.629	91.995
O2 HEX DISCH TEMP - DEGR	=	582.170	302.000	195.306	195.991	198.864	198.923	198.338	232.851	201.660
O2 HEX DISCH PRESSURE - PSI	=	79.301	75.187	70.615	72.514	79.961	80.657	78.311	80.697	85.329
O2 HEX DISCH SAT TEMP - DEGR	=	198.161	196.778	195.174	195.850	198.378	198.606	197.833	198.619	200.096
O2 FLOWRATE - LBM/SEC	=	0.0	0.0	3.828	3.510	2.810	3.112	2.904	2.387	2.571
O2 HEX DISCH ENTH - BTU/LBM	=	244.709	182.537	157.253	157.324	157.662	157.638	157.616	166.277	158.113
O2 HEX INLET ENTH - BTU/LBM	=	67.367	64.295	62.805	62.887	62.957	63.201	63.305	63.392	63.329
O2 CALC FLOW RATE - LBM/S	=	0.842	2.021	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O2 PRESSURE LOSS - PSI	=	5.259	8.160	6.385	11.664	6.652	5.152	8.082	7.061	6.811
O2 TEMP RISE - DEGR	=	405.306	132.648	29.621	30.108	32.817	32.271	31.432	65.737	34.716
H2 HEAT FLUX - BTU/S	=	149.249	239.004	270.654	269.885	230.884	165.447	263.140	282.380	269.987
O2 HEAT FLUX - BTU/S	=	149.249	239.004	361.549	331.476	266.122	293.887	273.878	245.589	243.689
O2 EXIT QUALITY	=	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
FLOW RATIO - OXY/FUEL	=	NA	NA	21.75	19.83	19.79	32.08	17.18	12.43	14.69
H2 HEX MEAS PRESS LOSS - PSI	=	2.16	1.85	1.50	1.54	1.08	0.54	1.45	1.84	1.56
RANGE	=	2.1/2.3	1.8/1.9	1.5/1.5	1.5/1.6	1.1/1.1	.51/.77	1.4/1.5	1.8/1.9	1.4/1.6
O2 HEX MEAS PRESS LOSS - PSI	=	5.26	8.16	NA	11.88	6.65	5.15	8.08	7.06	6.81
RANGE	=	3.8/6.4	6.9/9.3	NA/12.8	11.5/11.9	6.5/6.8	4.9/5.5	7.9/8.2	6.9/7.3	6.5/7.0
O2 OSCILLATION - LBMD/S	=	>7.1	>6.1	.17	.37	.28	.13	.18	.45	.25

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Table 1

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HYDROGEN / OXYGEN HEAT EXCHANGER SECOND UNIT TEST DATA

UNITED AIRCRAFT PRODUCTS, TANK HEAD IDLE, INVERTED POSITION

		PT 17	PT 18	PT 19	PT 20	PT 21	PT 22
H2 HEX INLET TEMP - DEGR	=	596.848	599.389	601.304	601.877	599.275	602.898
H2 HEX INLET PRESSURE - PSI	=	16.156	18.884	24.127	25.828	23.042	15.014
H2 HEX DISCH TEMP - DEGR	=	478.162	525.185	549.078	556.665	551.816	381.225
H2 HEX DISCH PRESSURE - PSI	=	15.953	18.203	22.857	24.444	21.933	15.055
H2 FLOWRATE - LBM/SEC	=	0.041	0.071	0.112	0.122	0.103	0.025
H2 HEX INLET ENTH - BTU/LBM	=	2005.879	2014.840	2021.647	2023.685	2014.511	2027.079
H2 HEX DISCH ENTH - BTU/LBM	=	1584.209	1752.850	1837.710	1864.562	1847.382	1225.590
H2 HEX PRESSURE LOSS - PSI	=	0.323	0.790	1.471	1.630	1.326	0.100
H2 HEX TEMP DROP - DEGR	=	118.686	74.204	52.226	45.212	47.459	221.673
O2 HEX INLET TEMP - DEGR	=	173.717	173.791	174.443	175.648	174.526	173.566
O2 HEX INLET PHASE	=	1.000	2.000	2.000	2.000	2.000	2.000
O2 HEX INLET SAT TEMP - DEGR	=	173.918	173.743	173.962	174.982	174.230	173.246
O2 HEX INLET PRESSURE - PSI	=	27.449	27.209	27.510	28.944	27.882	26.536
O2 HEX DISCH TEMP - DEGR	=	596.752	600.587	598.181	600.813	601.818	594.815
O2 HEX DISCH PRESSURE - PSI	=	27.150	26.939	27.272	28.680	27.614	26.262
O2 HEX DISCH SAT TEMP - DEGR	=	173.700	173.545	173.789	174.797	174.037	173.041
O2 FLOWRATE - LBM/SEC	=	0.0	0.0	0.0	0.0	0.0	0.0
O2 HEX DISCH ENTH - BTU/LBM	=	248.269	249.119	248.585	249.159	249.388	247.846
O2 HEX INLET ENTH - BTU/LBM	=	65.993	154.507	154.645	154.841	154.640	154.498
O2 CALC FLOW RATE - LBM/S	=	0.095	0.196	0.219	0.206	0.181	0.215
O2 PRESSURE LOSS - PSI	=	0.106	0.108	0.101	0.106	0.100	0.094
O2 TEMP RISE - DEGR	=	423.035	426.796	423.738	425.165	427.292	421.249
H2 HEAT FLUX - BTU/S	=	17.288	18.572	20.581	19.392	17.188	20.037
O2 HEAT FLUX - BTU/S	=	17.288	18.572	20.581	19.392	17.188	20.037
O2 EXIT QUALITY	=	1.000	1.000	1.000	1.000	1.000	1.000
FLOW RATIO - OXY/FUEL	=	NA	NA	NA	NA	NA	NA
H2 HEX MEAS PRESS LOSS - PSI	=	.32	.79	1.47	1.63	1.33	.10
RANGE	=	.31/.34	.75/.97	1.4/1.8	1.6/1.6	1.3/1.3	.10/.11
O2 HEX MEAS PRESS LOSS - PSI	=	.11	.11	.10	.11	.10	.09
RANGE	=	.08/.14	.08/.15	.07/.13	.08/.14	.13/.08	.07/.13
O2 OSCILLATION - LBMD/S	=	>.37	>.42	>.53	>.44	>.39	>.43

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Table 1 (cont.)

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6208C

HYDROGEN / OXYGEN HEAT EXCHANGER SECOND UNIT TEST DATA

ALPHA UNITED, PUMPED IDLE, UPRIGHT POSITION

		PT 38	PT 39	PT 40	PT 41	PT 42	PT 43	PT 44	PT 45	PT 46	PT 47
H2 HEX INLET TEMP - DEGR	=	622.205	621.778	621.673	621.915	634.130	678.802	619.899	612.330	629.132	619.660
H2 HEX INLET PRESSURE - PSI	=	25.818	24.968	26.153	24.794	21.836	18.732	25.331	28.838	27.219	27.368
H2 HEX DISCH TEMP - DEGR	=	224.954	210.988	236.315	219.015	209.175	182.808	218.013	229.450	236.275	224.706
H2 HEX DISCH PRESSURE - PSI	=	22.734	21.964	22.728	21.724	19.508	17.411	22.084	24.815	23.491	23.633
H2 FLOWRATE - LBM/SEC	=	0.171	0.170	0.173	0.166	0.137	0.105	0.172	0.202	0.184	0.190
H2 HEX INLET ENTH - BTU/LBM	=	2094.884	2093.375	2093.028	2093.851	2136.503	2292.250	2086.806	2060.371	2119.134	2086.006
H2 HEX DISCH ENTH - BTU/LBM	=	624.026	573.833	665.971	602.502	567.519	478.410	598.883	640.467	665.805	623.096
H2 HEX PRESSURE LOSS - PSI	=	3.271	3.163	3.622	3.246	2.470	1.447	3.442	4.243	3.910	3.937
H2 HEX TEMP DROP - DEGR	=	397.251	410.790	385.358	402.900	424.955	495.994	401.886	382.880	392.857	394.954
O2 HEX INLET TEMP - DEGR	=	167.969	166.588	166.705	166.325	165.851	165.687	165.683	165.816	165.681	165.953
O2 HEX INLET PHASE	=	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
O2 HEX INLET SAT TEMP - DEGR	=	199.706	199.296	200.763	200.089	200.196	200.635	200.101	200.158	201.647	201.023
O2 HEX INLET PRESSURE - PSI	=	84.089	82.797	87.482	85.307	85.648	87.067	85.344	85.528	90.396	88.334
O2 HEX DISCH TEMP - DEGR	=	194.931	193.811	248.802	196.429	197.232	198.978	196.346	195.773	240.875	196.985
O2 HEX DISCH PRESSURE - PSI	=	70.919	67.876	80.678	75.039	76.863	81.023	74.814	73.862	82.947	77.146
O2 HEX DISCH SAT TEMP - DEGR	=	195.283	194.177	198.613	196.727	197.348	198.725	196.650	196.321	199.344	197.444
O2 FLOWRATE - LBM/SEC	=	3.326	3.777	2.077	3.000	2.879	2.418	3.001	2.911	2.229	3.078
O2 HEX DISCH ENTH - BTU/LBM	=	127.910	121.258	170.109	133.271	126.454	157.632	135.244	146.477	168.140	139.821
O2 HEX INLET ENTH - BTU/LBM	=	63.733	63.171	63.225	63.068	62.876	62.812	62.808	62.862	62.815	62.922
O2 CALC FLOW RATE - LBM/S	=	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O2 PRESSURE LOSS - PSI	=	0.0	0.0	6.994	10.662	9.093	6.315	10.960	0.032	7.679	11.593
O2 TEMP RISE - DEGR	=	26.962	27.223	82.097	30.104	31.381	33.291	30.663	29.957	75.194	31.032
H2 HEAT FLUX - BTU/S	=	251.121	258.114	246.320	247.774	215.341	189.660	255.742	286.359	267.918	278.466
O2 HEAT FLUX - BTU/S	=	213.453	219.397	221.997	210.608	183.040	229.274	217.381	243.405	234.769	236.696
O2 EXIT QUALITY	=	0.643	0.566	1.000	0.705	0.620	1.000	0.729	0.867	1.000	0.784
FLOW RATIO - OXY/FUEL	=	19.45	22.22	12.01	18.07	21.01	23.03	17.45	13.35	11.15	16.20
H2 HEX MEAS PRESS LOSS - PSI	=	3.27	3.16	3.62	3.25	2.47	1.45	3.42	4.24	3.91	3.94
RANGE	=	3.2/3.3	3.1/3.2	3.6/3.7	2.9/3.3	2.0/2.6	1.1/2.8	3.2/3.9	4.2/4.3	3.9/4.0	3.9/4.0
O2 HEX MEAS PRESS LOSS - PSI	=	NA	NA	7.00	10.66	9.09	6.32	10.96	.03	7.68	11.6
RANGE	=	NA/12.8	NA/NA	5.8/8.5	10.5/11.1	8.8/9.3	5.5/6.9	10.7/11.0	.03/.03	7.3/8.0	11.3/11.8
O2 OSCILLATION - LBMD/S	=	1.02	.10	2.13	.26	.35	1.14	.41	.26	.39	.24

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Table 1 (cont.)

HYDROGEN / OXYGEN HEAT EXCHANGER SECOND UNIT TEST DATA

ALPHA UNITED, TANK HEAD IDLE, INVERTED POSITION

		PT 50	PT 51	PT 52	PT 53	PT 54	PT 55
H2 HEX INLET TEMP - DEGR	=	596.269	605.267	600.250	598.704	600.709	599.990
H2 HEX INLET PRESSURE - PSI	=	16.823	15.916	18.146	21.467	25.206	15.081
H2 HEX DISCH TEMP - DEGR	=	440.296	199.383	395.701	444.938	487.646	201.425
H2 HEX DISCH PRESSURE - PSI	=	16.157	15.558	16.979	19.532	22.645	15.019
H2 FLOWRATE - LBM/SEC	=	0.045	0.046	0.067	0.093	0.115	0.021
H2 HEX INLET ENTH - BTU/LBM	=	2003.859	2035.399	2017.847	2012.482	2019.579	2016.883
H2 HEX DISCH ENTH - BTU/LBM	=	1446.194	533.690	1280.320	1463.273	1618.516	540.712
H2 HEX PRESSURE LOSS - PSI	=	0.632	0.350	1.124	1.893	2.564	0.103
H2 HEX TEMP DROP - DEGR	=	155.973	405.884	204.549	153.766	113.063	398.565
O2 HEX INLET TEMP - DEGR	=	176.663	170.319	176.172	174.207	171.543	173.224
O2 HEX INLET PHASE	=	1.000	1.000	1.000	1.000	1.000	1.000
O2 HEX INLET SAT TEMP - DEGR	=	176.797	176.127	177.786	177.647	177.854	178.091
O2 HEX INLET PRESSURE - PSI	=	31.635	30.620	33.178	32.958	33.286	33.665
O2 HEX DISCH TEMP - DEGR	=	177.450	174.948	177.487	177.262	177.663	178.142
O2 HEX DISCH PRESSURE - PSI	=	31.327	28.922	32.466	32.189	32.627	33.480
O2 HEX DISCH SAT TEMP - DEGR	=	176.595	174.966	177.334	177.156	177.437	177.975
O2 FLOWRATE - LBM/SEC	=	0.0	0.808	0.454	0.504	0.443	0.364
O2 HEX DISCH ENTH - BTU/LBM	=	155.123	137.435	155.058	155.021	155.090	155.152
O2 HEX INLET ENTH - BTU/LBM	=	67.209	64.609	67.009	66.202	65.113	65.801
O2 CALC FLOW RATE - LBM/S	=	0.283	0.0	0.0	0.0	0.0	0.0
O2 PRESSURE LOSS - PSI	=	0.309	1.816	0.727	0.825	0.720	0.241
O2 TEMP RISE - DEGR	=	0.787	4.629	1.315	3.055	6.120	4.918
H2 HEAT FLUX - BTU/S	=	24.853	69.227	49.464	50.913	46.213	30.682
O2 HEAT FLUX - BTU/S	=	24.853	58.843	39.974	44.764	39.860	32.524
O2 EXIT QUALITY	=	1.000	0.804	1.000	1.000	1.000	1.000
FLOW RATIO - OXY/FUEL	=	NA	17.57	6.78	5.42	3.85	17.33
H2 HEX MEAS PRESS LOSS - PSI	=	.63	.35	1.12	1.89	2.56	.10
RANGE	=	.62/.65	.33/.36	1.1/1.2	1.9/1.9	2.5/2.6	.10/.11
O2 HEX MEAS PRESS LOSS - PSI	=	.31	1.82	.73	.83	.72	.24
RANGE	=	.18/.48	1.1/2.4	.63/.91	.67/.97	.61/.81	.15/.36
O2 OSCILLATION - LBMD/S	=	>1.32	.40	.31	.22	.38	.34

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Table 1 (cont.)

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HEAT EXCHANGER ANALYSIS

HEADER	TANK HEAD IDLE			PUMPED IDLE				
	SPEC	#1 UAP PT 138	#1 AU PT 119	SPEC	#1 UAP PT 156	#2 UAP PT 16	#1 AU PT 105	#2 AU PT 40
HHIP PSIA	9.0	19.2	14.8	46.7	25.5	22.6	32.2	26.3
HHIT DEGR	594.	606.	607.	659.	635.	638.	632.	622.
OHIP PSIA	20.	26.4	29.3	110.	90.	92.	88.	87.
OHIT DEGR	165.8	172.1	173.6	168.	169.	167.	167.	167.
HDELP PSID	2.1	.95	.02	2.4	1.7	1.4	4.7	3.7
RANGE	———	.92/.97	.02/.03	———	1.6/1.8	1.3/1.4	4.5/5.0	3.5/3.8
ODELP PSID	2.3	2.4	.81	4.7	6.4	6.7	9.2	7.0
RANGE	———	2.2/2.7	.75/.86	———	6.2/6.6	6.5/7.0	7.6/11.5	5.8/8.5
HFLO LBM/S	.094	.096	.015	.190	.188	.161	.205	.174
RANGE	———	.095/.096	.014/.016	———	.182/.193	.160/.163	.197/.213	.170/.179
OFLO LBM/S	.31	.52	.30	2.84	2.56	2.76	2.51	2.03
RANGE	———	.472/.584	.292/.309	———	2.13/2.83	2.72/2.79	1.93/3.03	.96/3.09
RATIO O/F	3.30	5.42	20.0	14.95	13.62	17.14	12.24	11.67
OSC RANGE LBMD/S	.10	.11	.02	.40	.71	.07	1.1	2.1
O2 QUAL	.95	1.0	1.0	.95	1.0	1.0	1.0	1.0

FEBRUARY 16, 1987
RAY KALDOR

TABLE 2

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Table 3

HYDROGEN OXYGEN HEAT EXCHANGER ANALYSIS
COMPARISON BY MANUFACTURER FOR
PERFORMANCE REPEATABILITY

ALPHA UNITED UNIT #1 PUMPED IDLE OPERATION (REFERENCE 2)

	PT105	PT106	PT108
H2 HEX INLET PRESS - PSI	31.4	32.1	30.5
O2 HEX INLET PRESS - PSI	88.4	88.3	89.0
H2 FLOWRATE - LBM/S	.200	.206	0.193
O2 FLOWRATE - LBM/S	2.595	2.464	2.225
FLOW RATIO OXY/HYD	12.98	11.96	11.53
H2 HEX PRESS LOSS - PSID (2.4 MAX)	4.5	4.8	4.5
O2 HEX PRESS LOSS - PSID (4.7 MAX)	9.6	9.0	7.6
O2 FLOWRATE OSCIL - LBMD/S (.40 MAX)	0.99	2.22	1.22
QUALITY	1.00	1.00	1.00

ALPHA UNITED UNIT #2 PUMPED IDLE OPERATION

	PT 38	PT 39	PT 40	PT 41	PT 42	PT 43	PT 44	PT 45	PT 46	PT 47
H2 HEX INLET PRESS - PSI	25.8	25.0	26.2	24.8	21.8	18.7	25.3	28.8	27.2	27.4
O2 HEX INLET PRESS - PSI	84.1	82.9	87.5	85.3	85.6	87.1	85.3	85.5	90.4	88.3
H2 FLOWRATE - LBM/S	0.171	0.170	0.173	0.166	0.137	0.105	0.172	0.202	0.184	0.190
O2 FLOWRATE - LBM/S	3.326	3.777	2.077	3.000	2.879	2.418	3.001	2.911	2.229	3.079
FLOW RATIO OXY/HYD	19.45	22.22	12.01	18.07	21.01	23.03	17.45	13.45	11.15	16.20
H2 HEX PRESS LOSS - PSID (2.4 MAX)	3.3	3.2	3.6	3.3	2.5	1.5	3.4	4.2	3.9	3.9
O2 HEX PRESS LOSS - PSID (4.7 MAX)	13.2	14.9	7.0	10.7	9.1	6.3	11.0	.0	7.7	11.6
O2 FLOWRATE OSCIL - LBMD/S (.40 MAX)	1.02	0.10	2.13	0.26	0.35	1.14	0.41	0.26	0.39	0.24
QUALITY	.643	.566	1.00	.705	.620	1.00	.729	.867	1.00	.784

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Table 3
(Cont'd)

HYDROGEN/OXYGEN HEAT EXCHANGER ANALYSIS
COMPARISON BY MANUFACTURER FOR
PERFORMANCE REPEATABILITY

UNITED AIRCRAFT PRODUCTS UNIT #1 PUMPED IDLE OPERATION (REFERENCE 2)

	PT150	PT154	PT155	PT156	PT157
H2 HEX INLET PRESS - PSI	25.9	28.2	25.7	25.3	29.6
O2 HEX INLET PRESS - PSI	87.1	87.9	86.8	90.5	90.4
H2 FLOWRATE - LBM/S	0.194	0.208	0.199	0.186	0.222
O2 FLOWRATE - LBM/S	2.537	2.287	2.696	2.573	2.664
FLOW RATIO OXY/HYD	13.08	11.00	13.55	13.83	12.00
H2 HEX PRESS LOSS - PSID (2.4 MAX)	1.8	2.2	1.7	1.7	2.3
O2 HEX PRESS LOSS - PSID (4.7 MAX)	7.0	6.1	5.8	6.4	7.5
O2 FLOWRATE OSCIL - LBMD/S (.40 MAX)	.73	.50	.26	.40	.56
QUALITY	1.00	1.00	.994	1.00	1.00

UNITED AIRCRAFT PRODUCTS UNIT #2 PUMPED IDLE OPERATION

	PT 10	PT 11	PT 12	PT 13	PT 14	PT 15	PT 16
H2 HEX INLET PRESS - PSI	24.1	24.3	20.9	17.6	23.2	25.8	23.8
O2 HEX INLET PRESS - PSI	82.9	84.0	86.5	85.7	86.2	87.6	92.0
H2 FLOWRATE - LBM/S	0.176	0.177	0.142	0.097	0.169	0.192	0.175
O2 FLOWRATE - LBM/S	3.828	3.510	2.810	3.112	2.904	2.387	2.571
FLOW RATIO OXY/HYD	21.75	19.83	19.79	32.08	17.18	12.43	14.69
H2 HEX PRESS LOSS - PSID (2.4 MAX)	1.5	1.5	1.1	0.5	1.5	1.8	1.6
O2 HEX PRESS LOSS - PSID (4.7 MAX)	12.2	11.9	6.7	5.2	8.1	7.1	6.8
O2 FLOWRATE OSCIL - LBMD/S (.40 MAX)	.17	.37	.28	.13	.18	.45	.25
QUALITY	1.00	1.00	1.00	1.00	1.08	1.00	1.00

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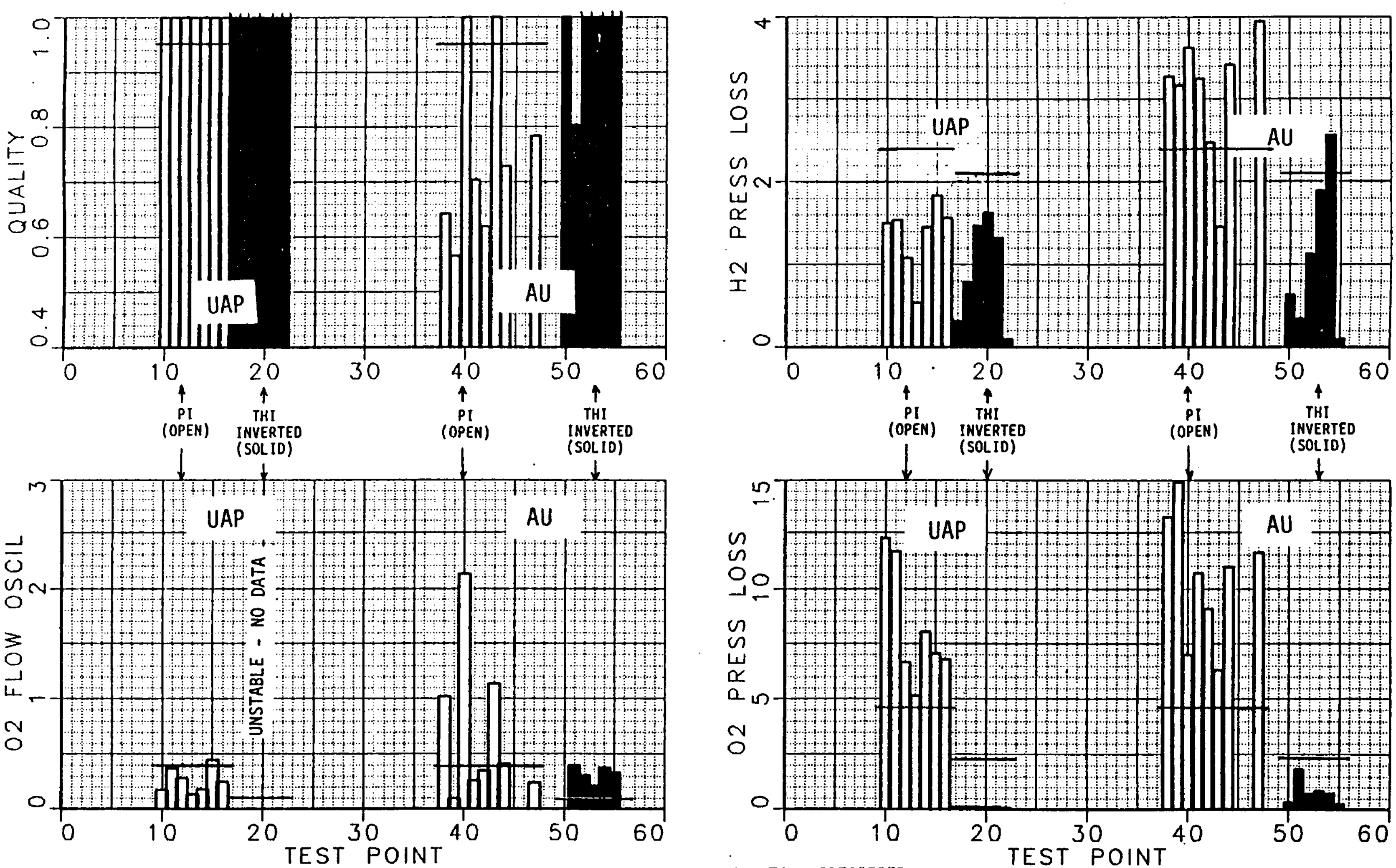
PRATT & WHITNEY –' ROCKET PERFORMANCE

UNIT 2 TEST SUMMARY. LINES INDICATE REQUIREMENTS OF REFERENCES 3 & 4.



CAUTION - AS TESTED RESULTS. SPECIFIED THI AND PI PRESSURES COULD NOT BE MET.

02/26/87
RBK

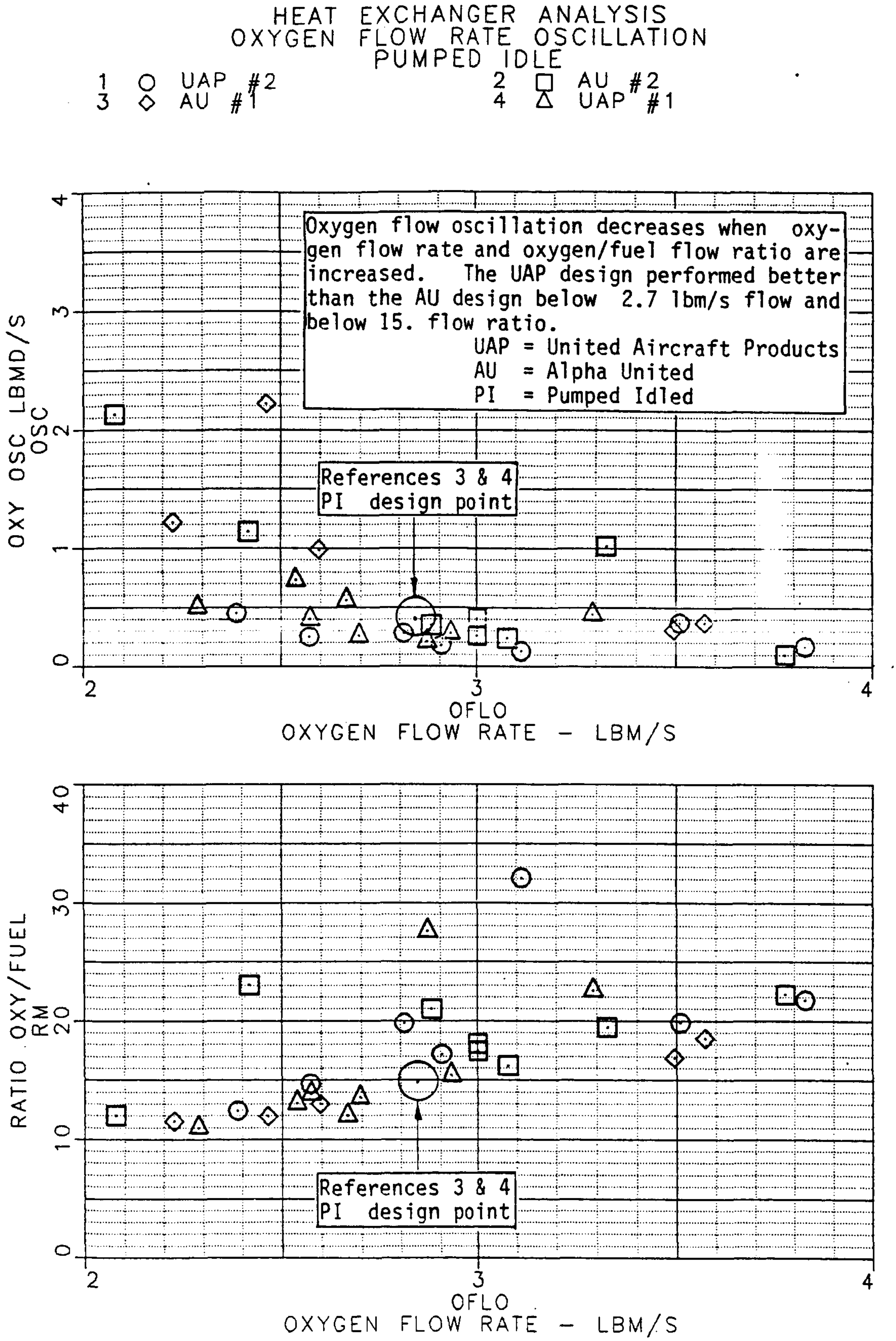
UAP = UNITED AIRCRAFT PRODUCTS
THI = TANK HEAD IDLE

AU = ALPHA UNITED
PI = PUMPED IDLE

Figure 1

ORIGINAL PAGE IS OF POOR QUALITY

6208C



02/05/87
KALDOR, RAY

Figure 2

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HEAT EXCHANGER ANALYSIS
OXYGEN FLOW RATE OSCILLATION
TANK HEAD IDLE

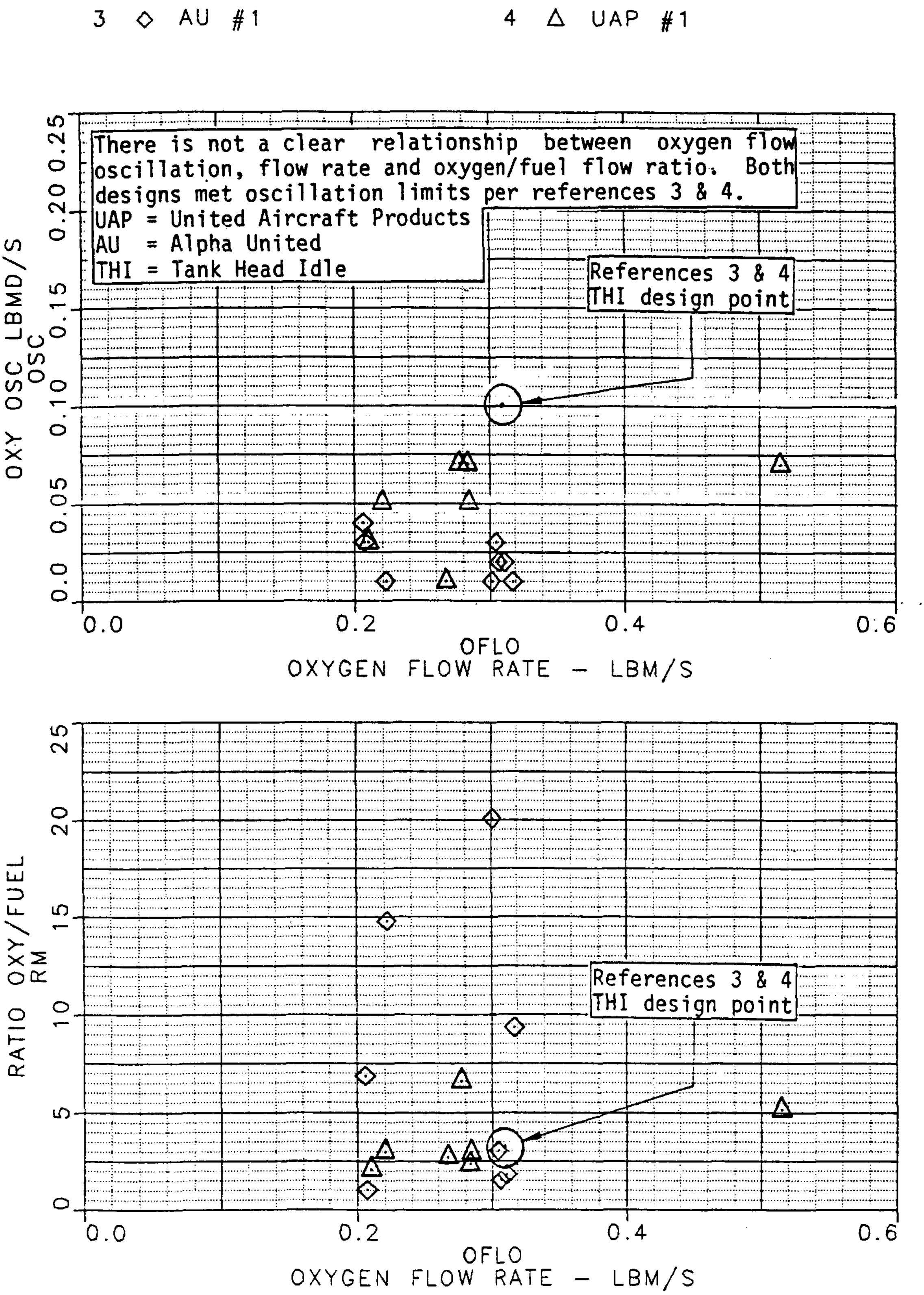

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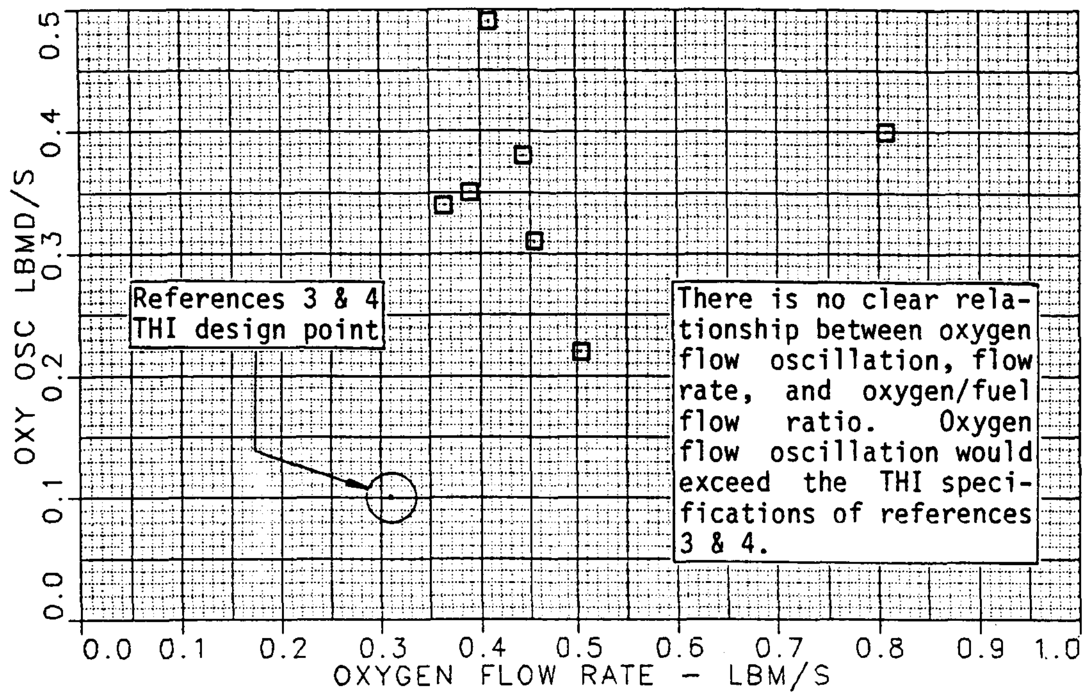
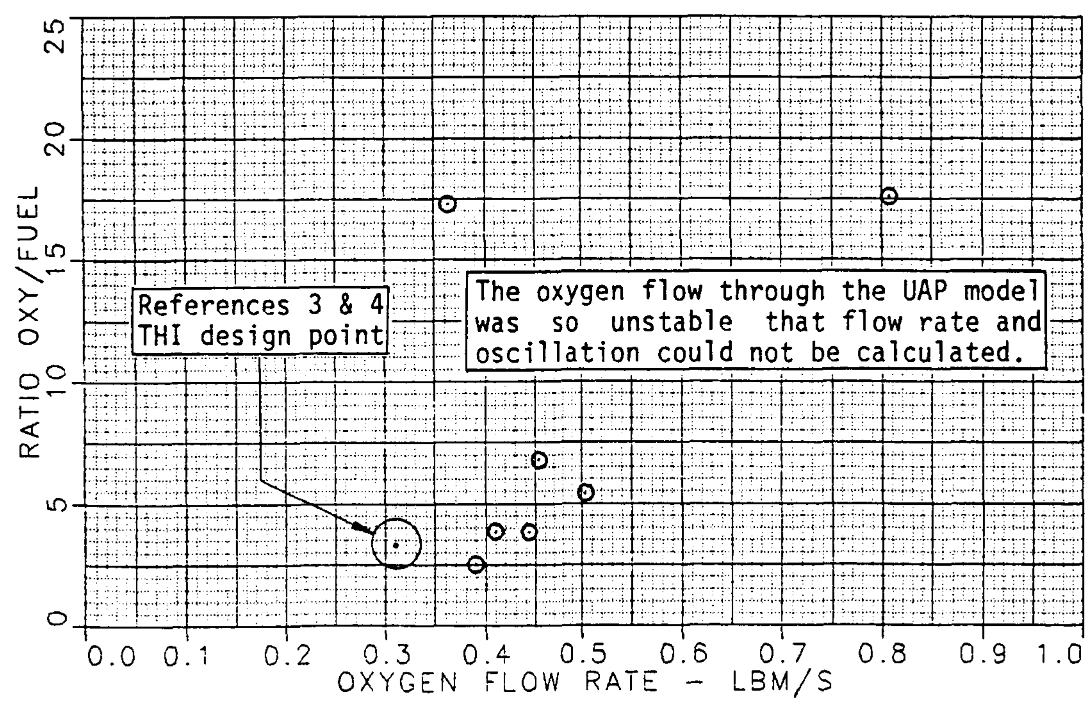
Figure 3

6208C

HEAT EXCHANGER ANALYSIS
OXYGEN FLOW RATE OSCILLATION
TANK HEAD IDLE - INVERTED

1 AU #2

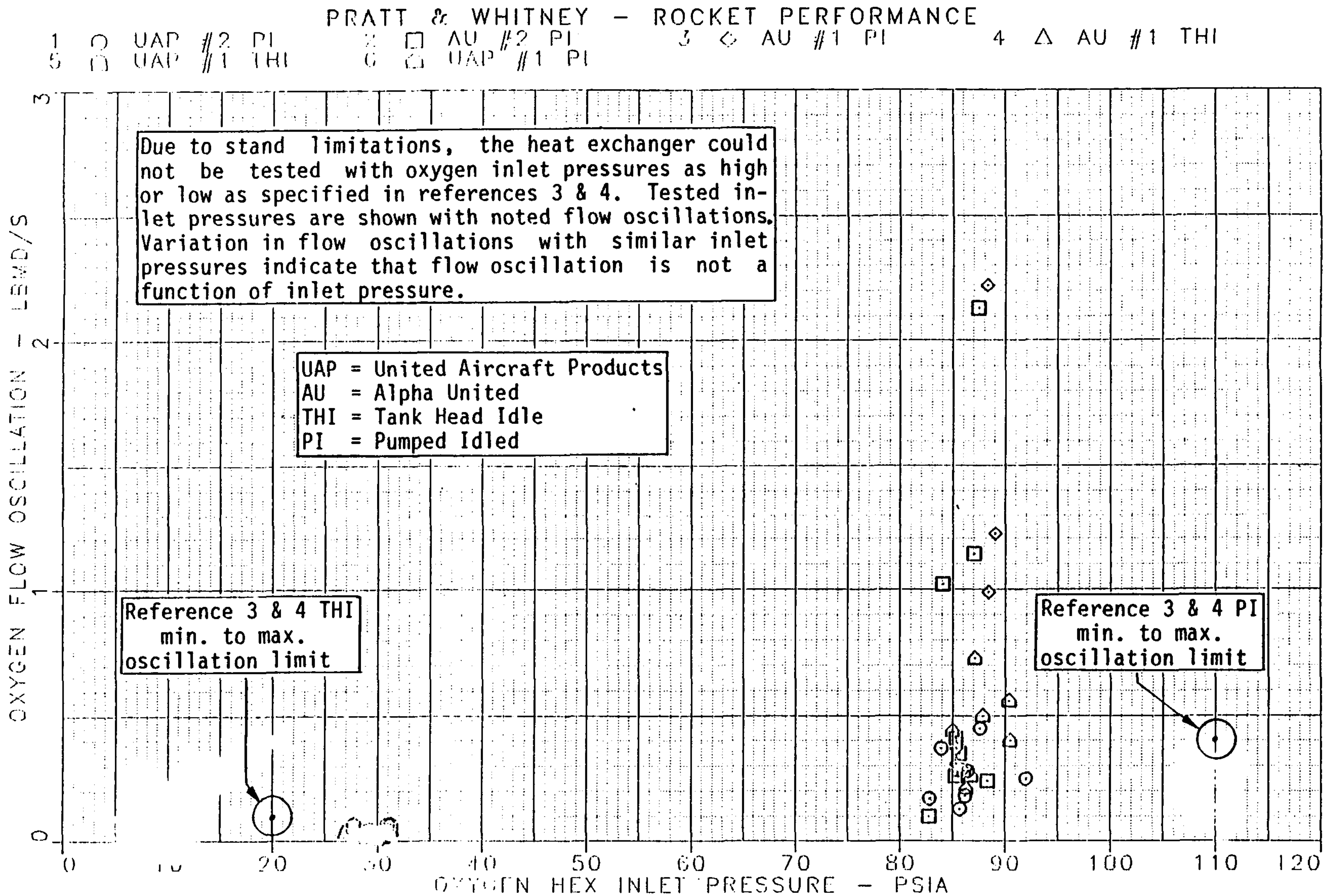




02/19/87
RBK

Figure 3A

6208C



02/13/87
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Figure 4

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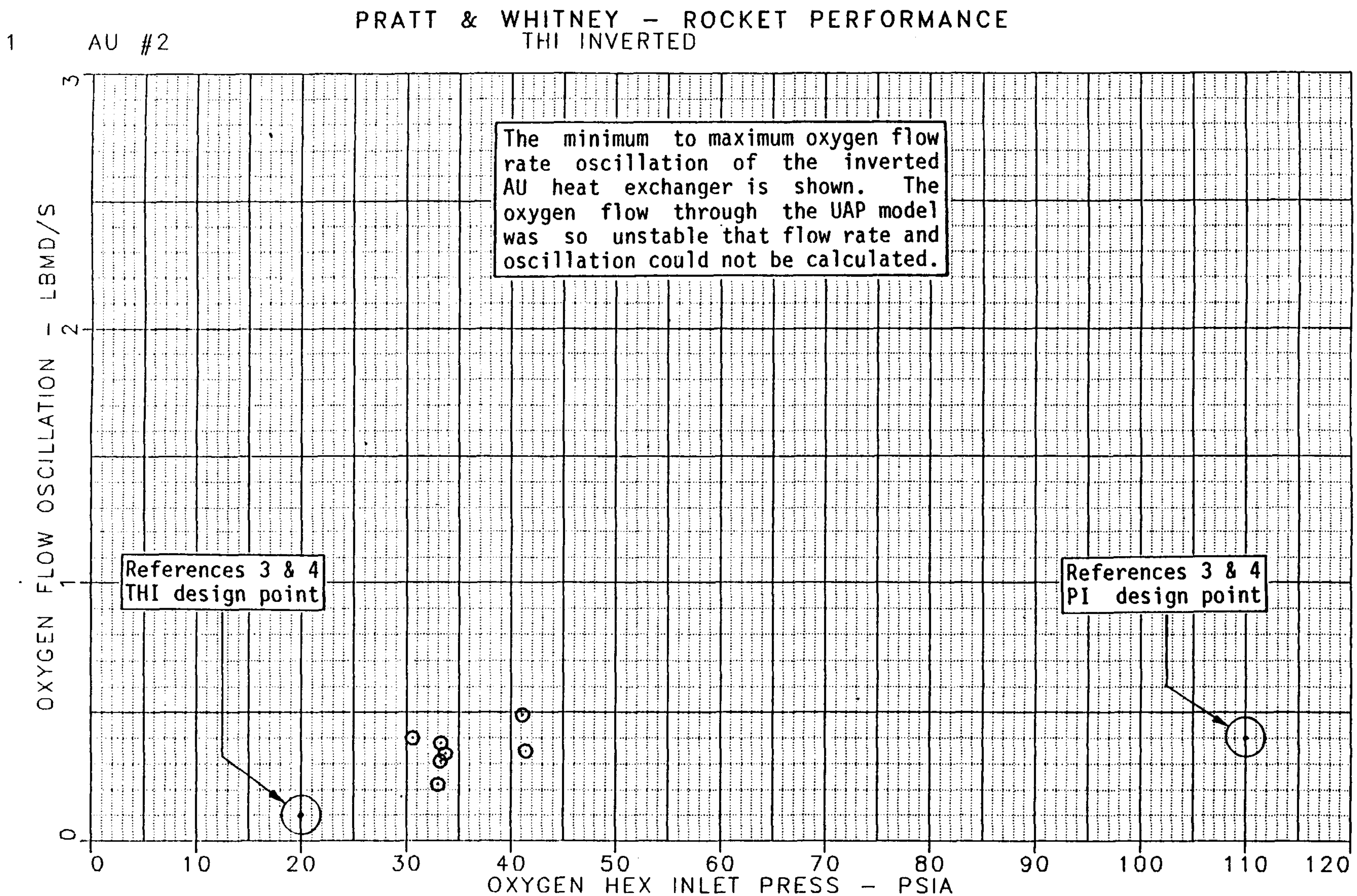

02/19/87
RBK

Figure 4A

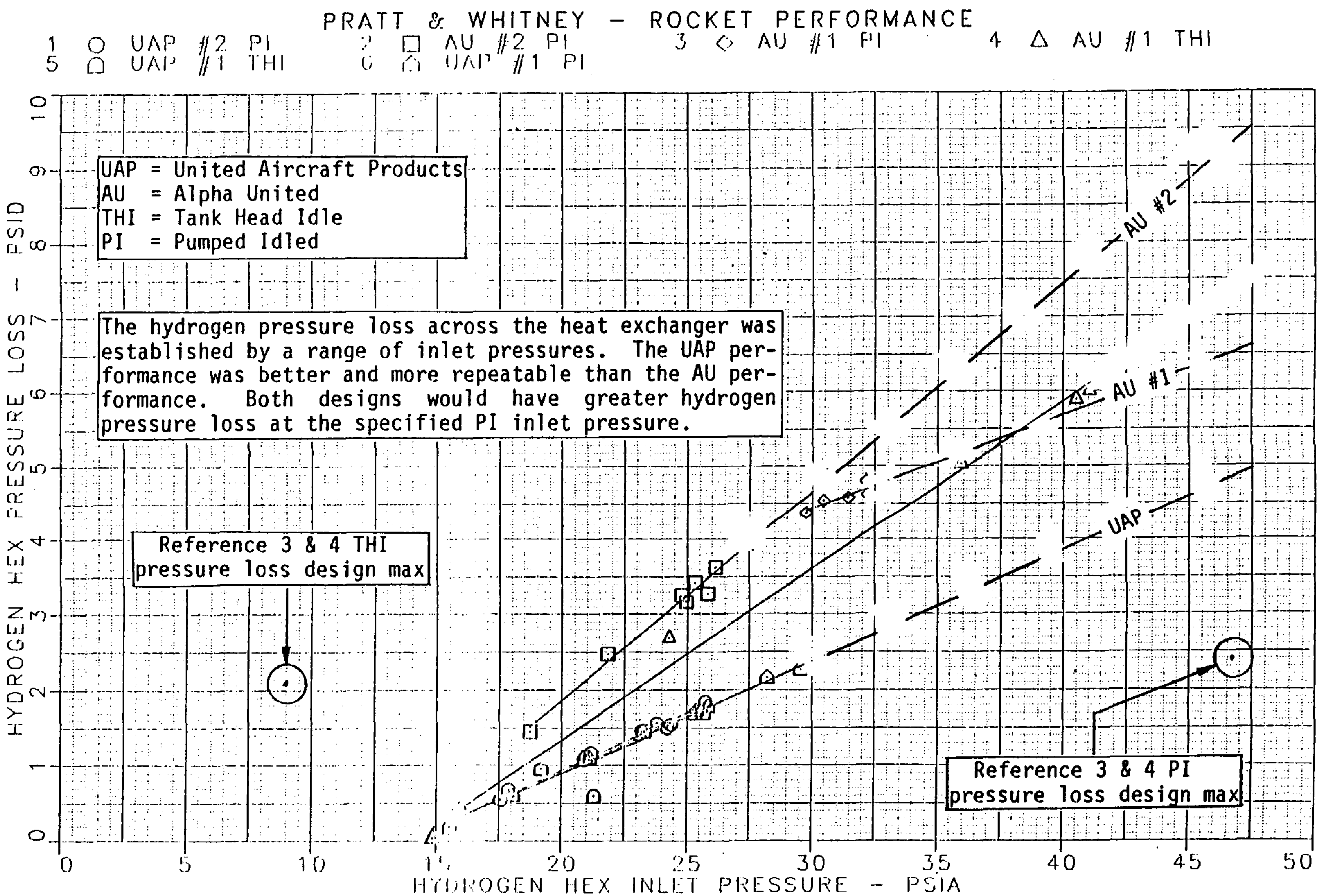

Figure 5

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PRATT & WHITNEY - ROCKET PERFORMANCE

1 AU #2 POINTS 51-55, 59, 60 THI INVERTED

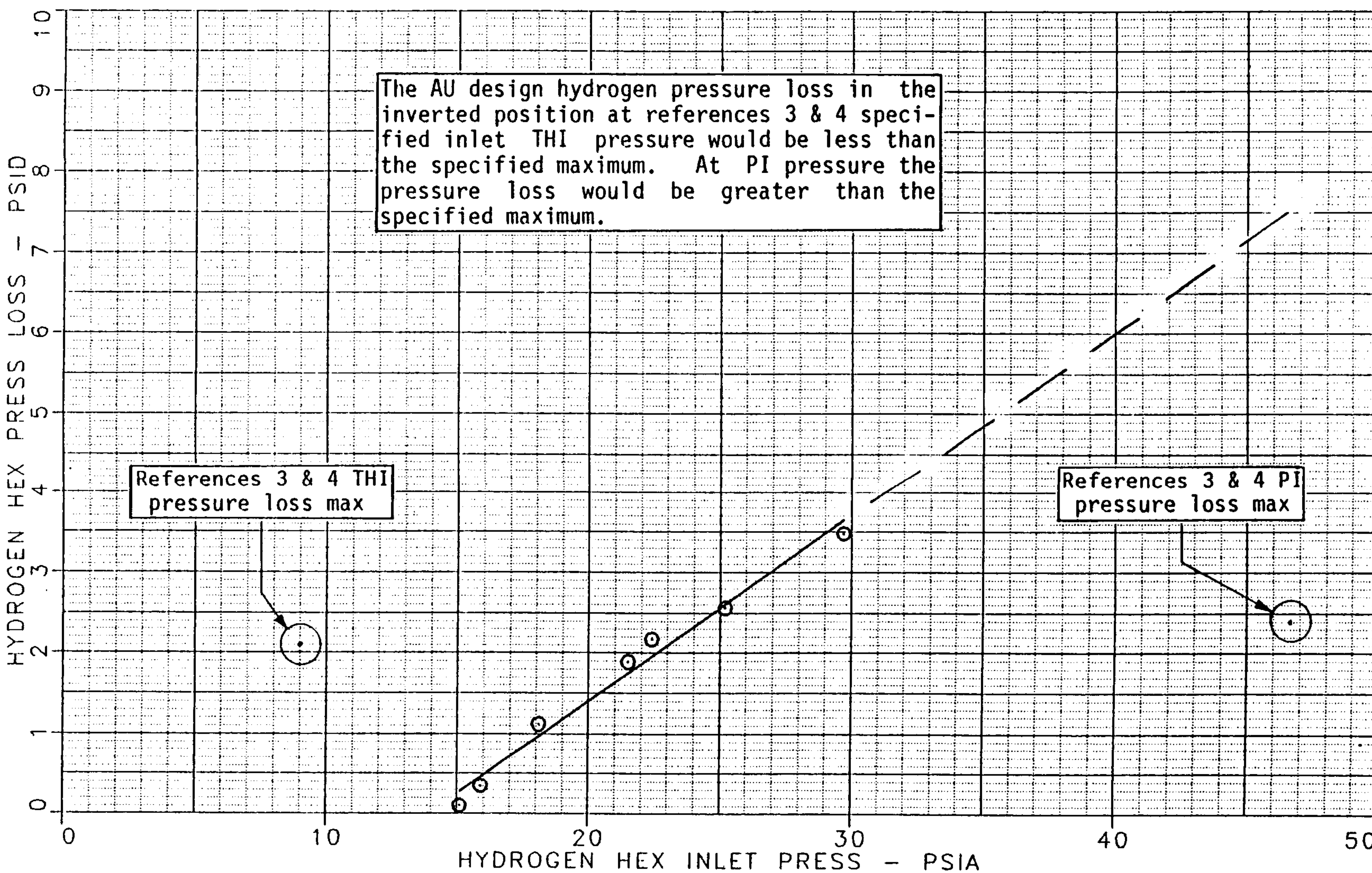

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Figure 5A

6208C

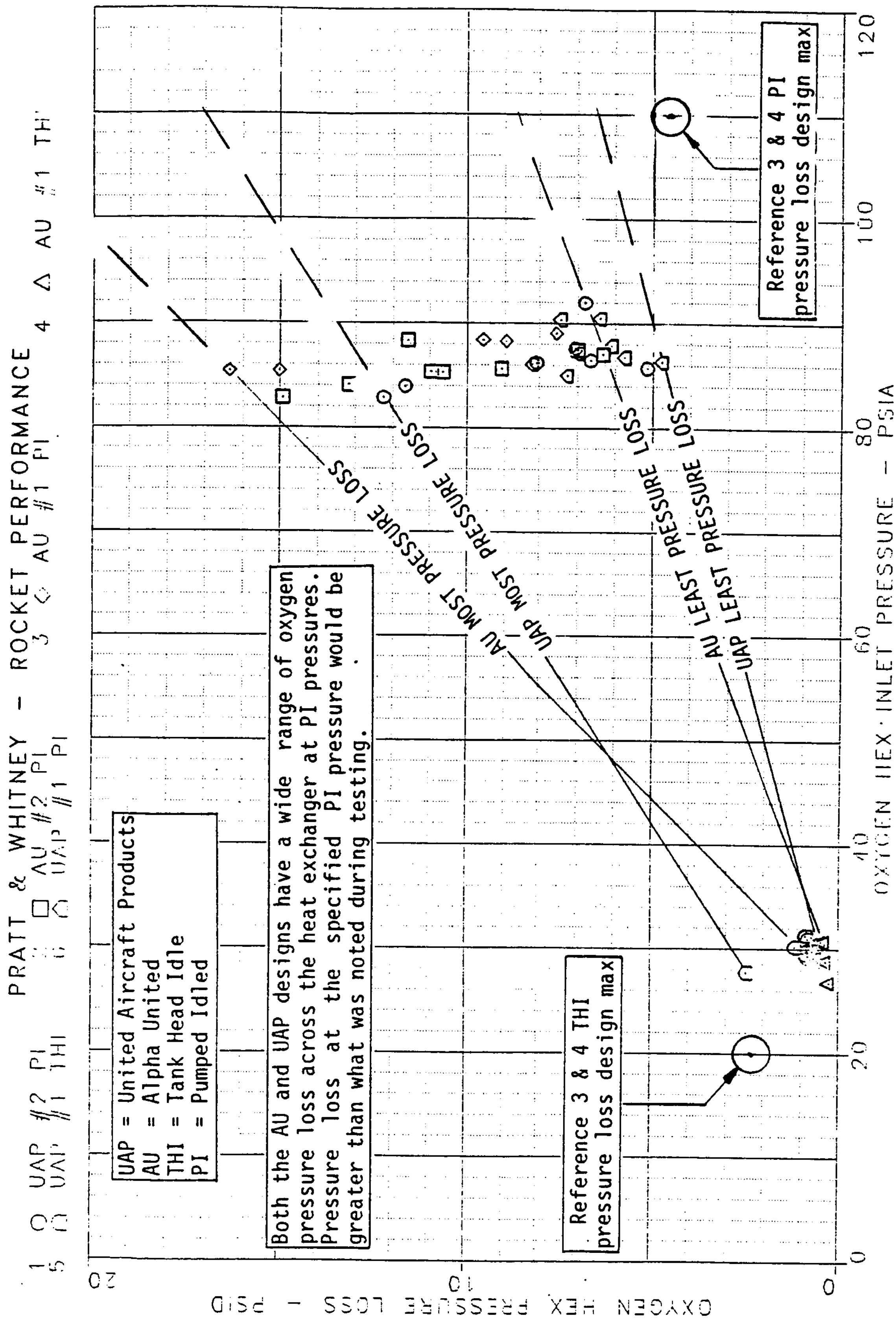

Figure 6

02/13/87
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6208C

PRATT & WHITNEY - ROCKET PERFORMANCE

1 AU #2 POINTS 51-55, 59, 60 THI INVERTED

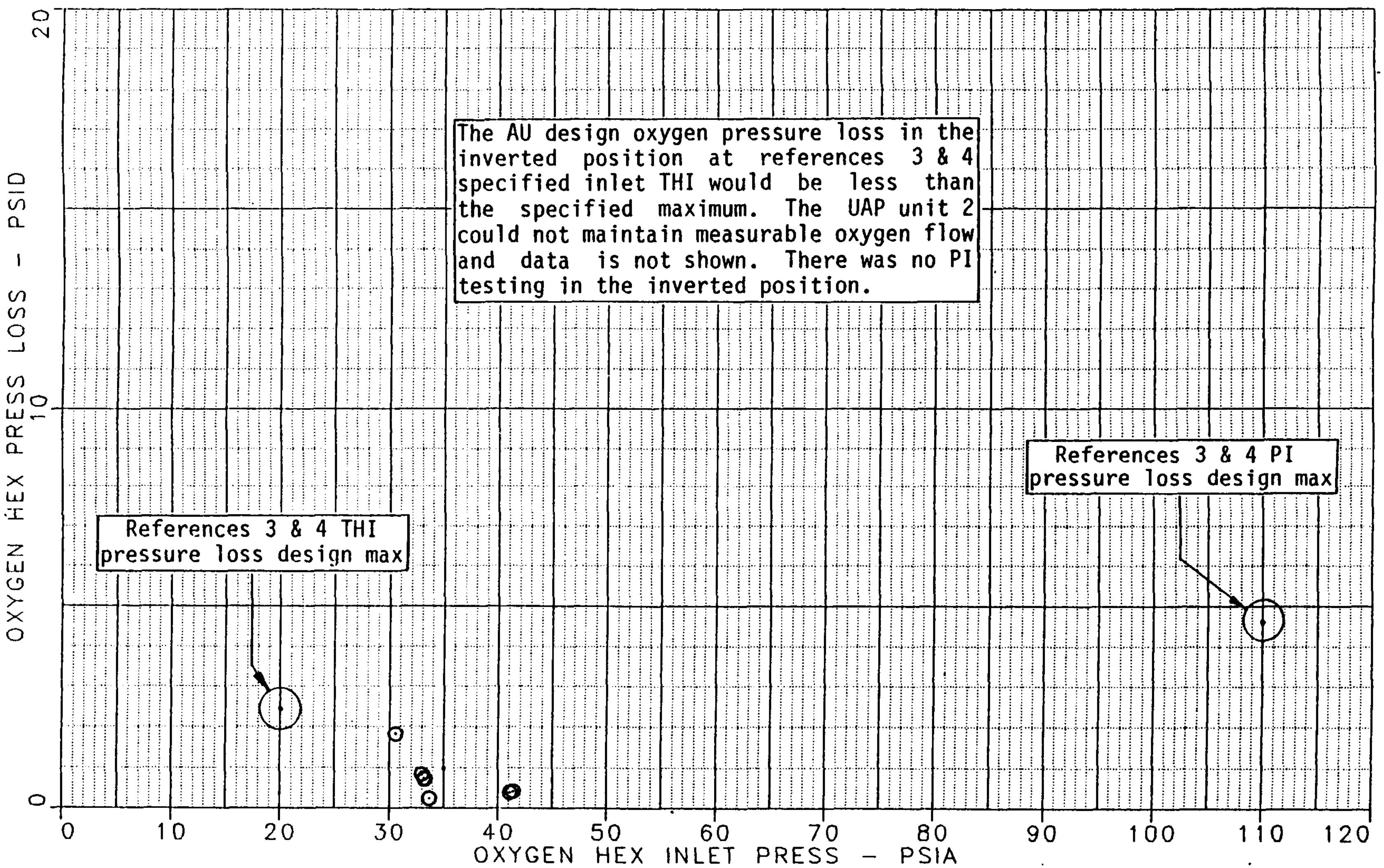

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Figure 6A

6208C

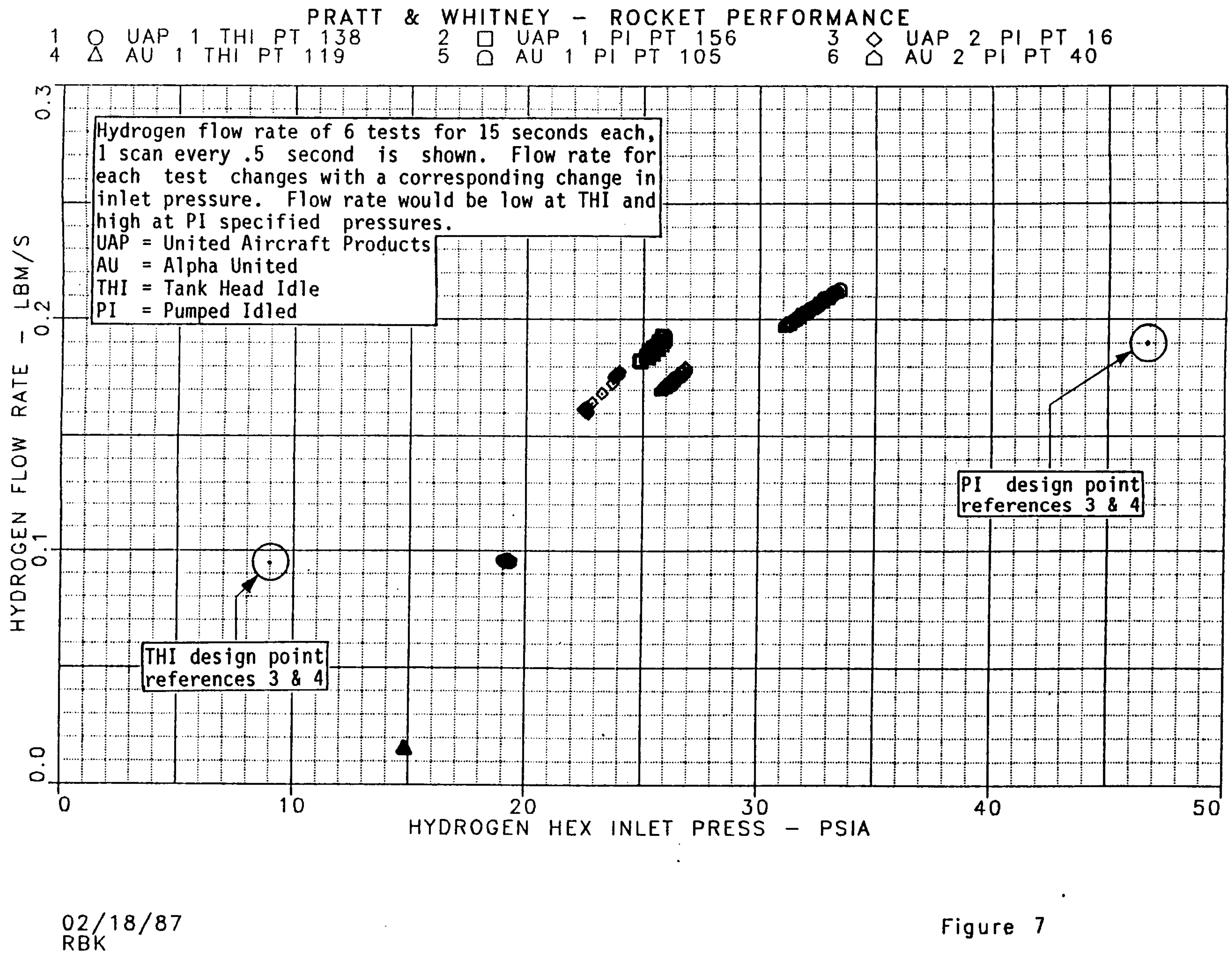
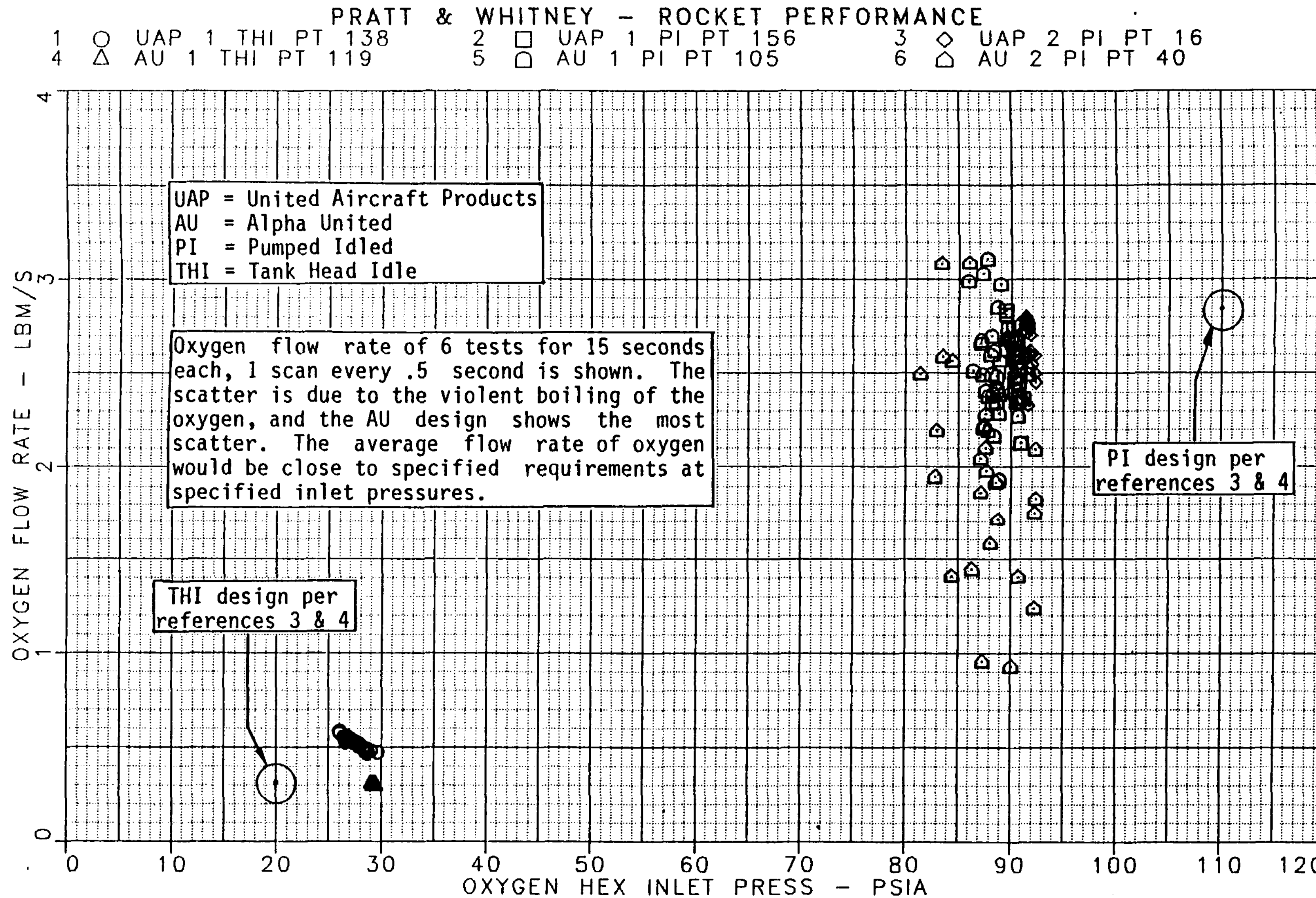


Figure 7

6208C



02/12/87
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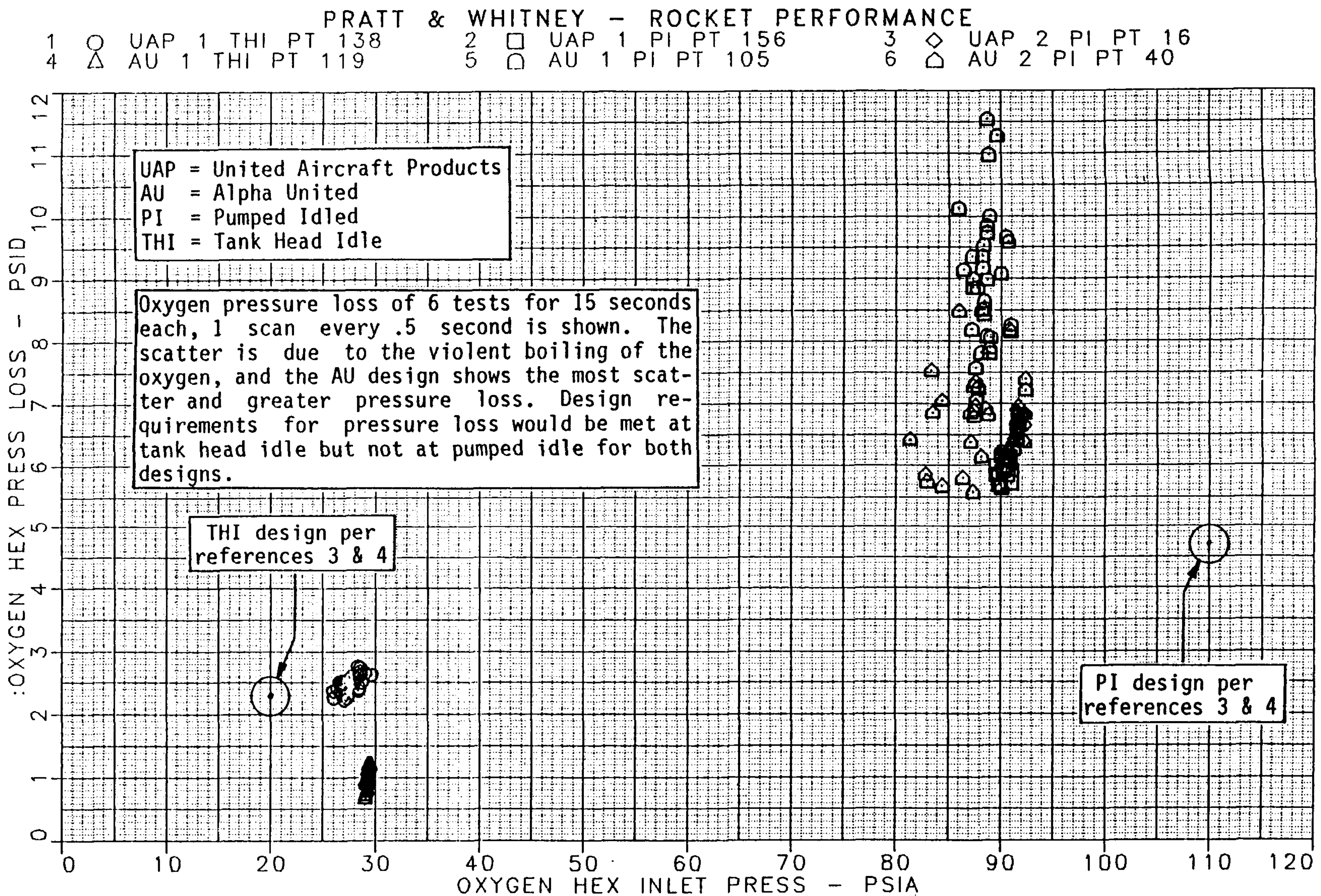
Figure 8

6208C



02/12/87
RBK

Figure 9

6208C

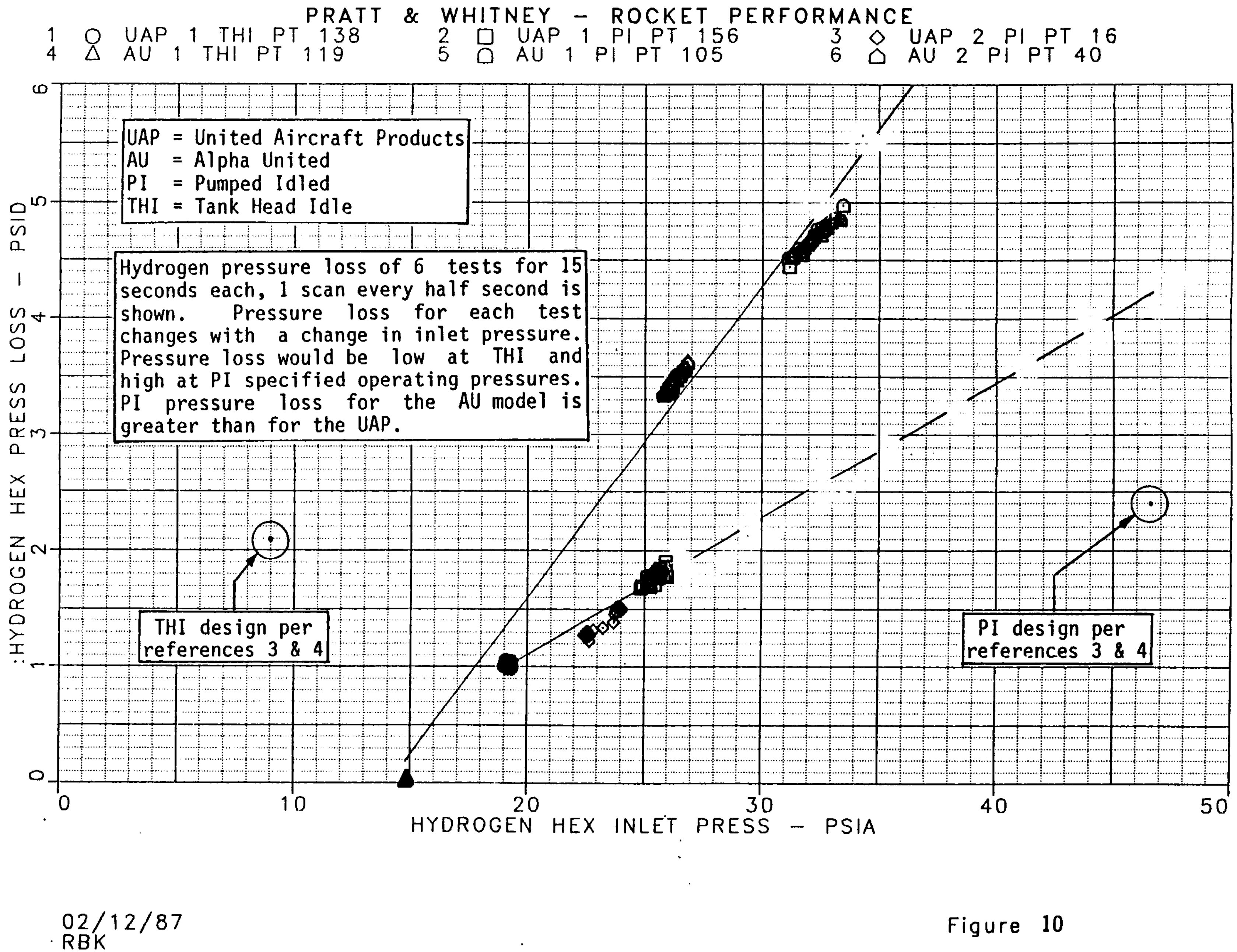


Figure 10

6208C

PRATT & WHITNEY - ROCKET PERFORMANCE

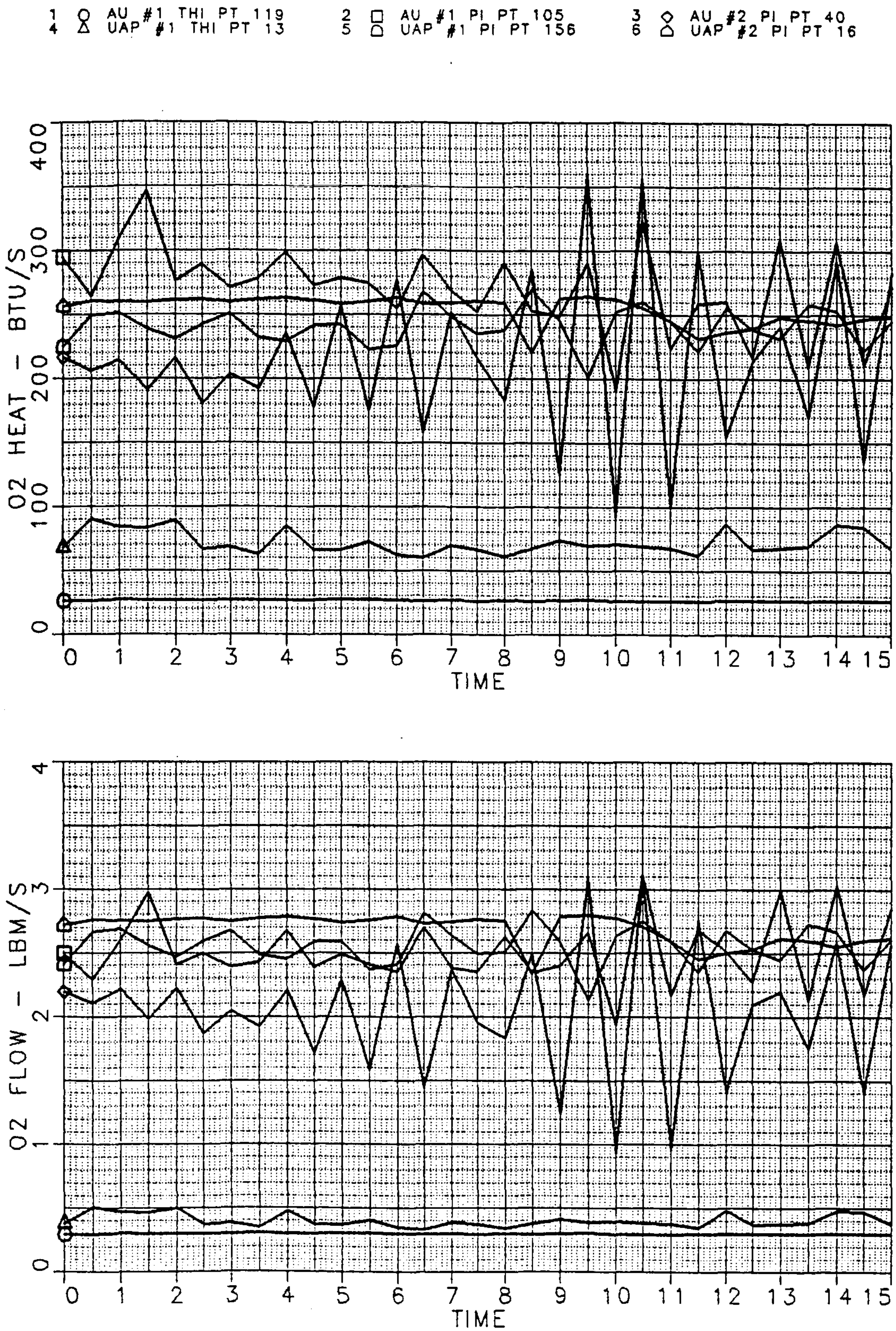


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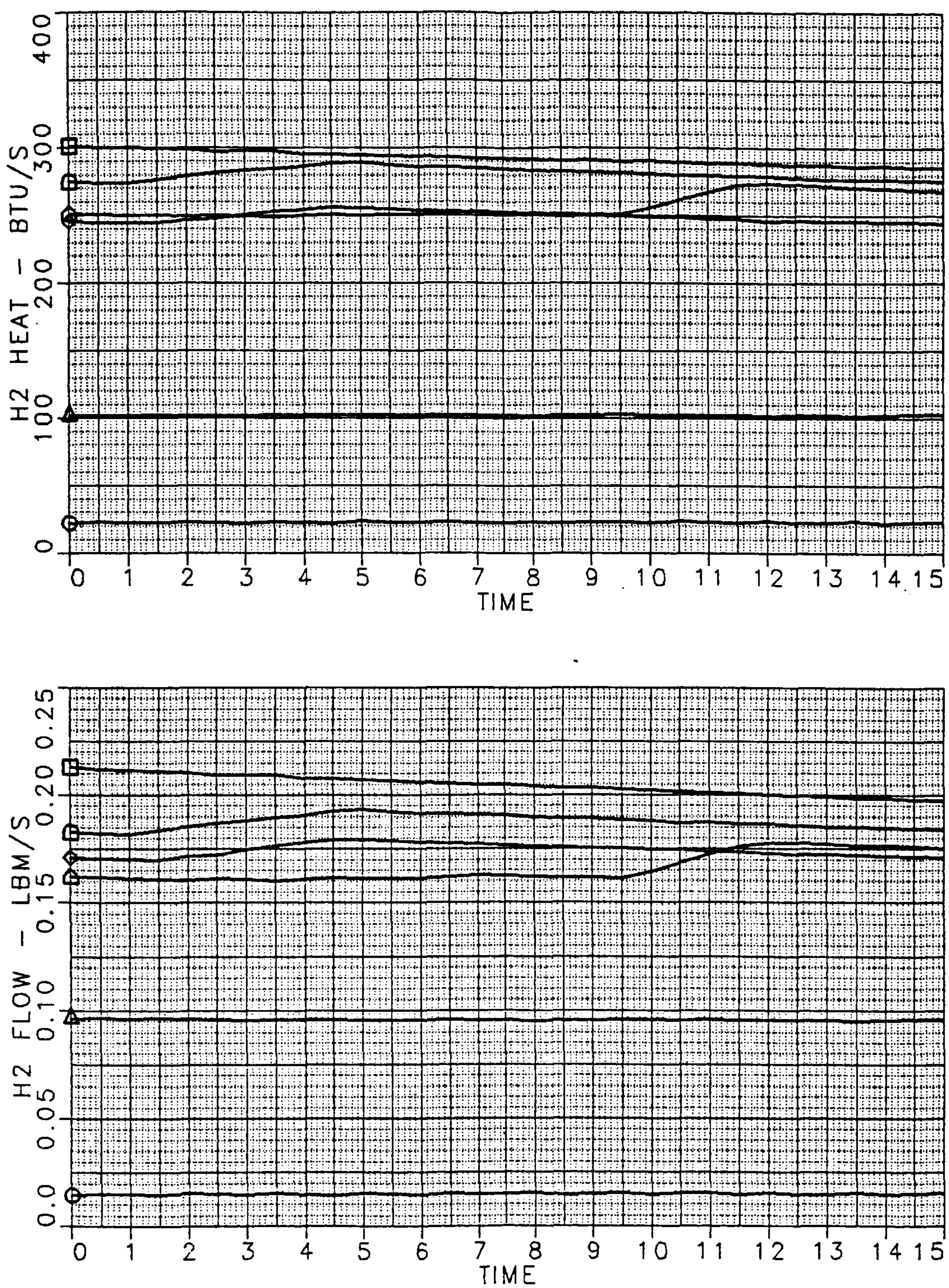
Figure 11

6208C

PRATT & WHITNEY - ROCKET PERFORMANCE

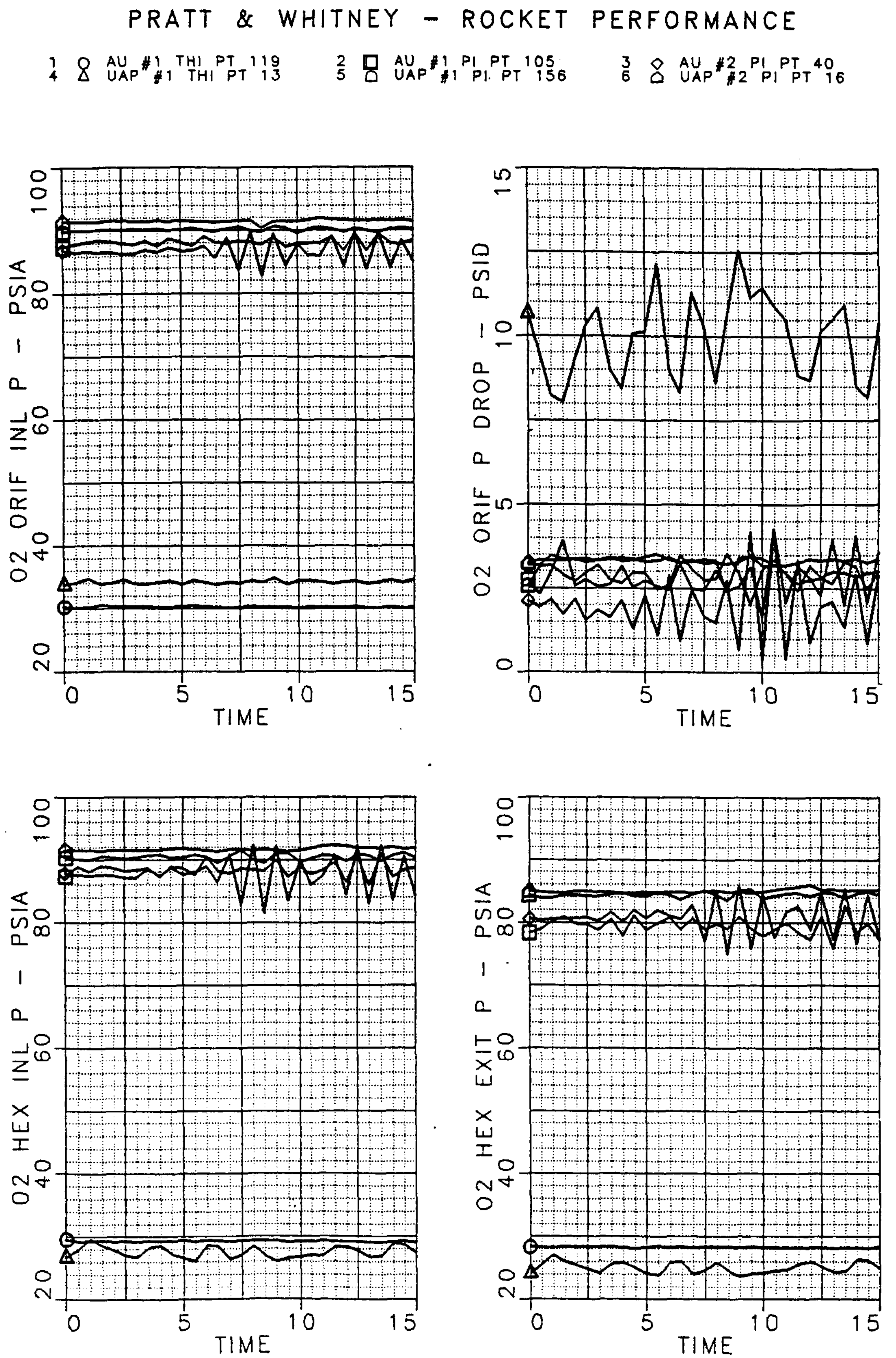
1 ○ AU #1 THI PT 119 | 2 □ AU #1 PI PT 105 | 3 ◇ AU #2 PI PT 40
4 △ UAP #1 THI PT 13 | 5 ⌂ UAP #1 PI PT 156 | 6 △ UAP #2 PI PT 16



03/02/87
RBK

Figure 12

6208C

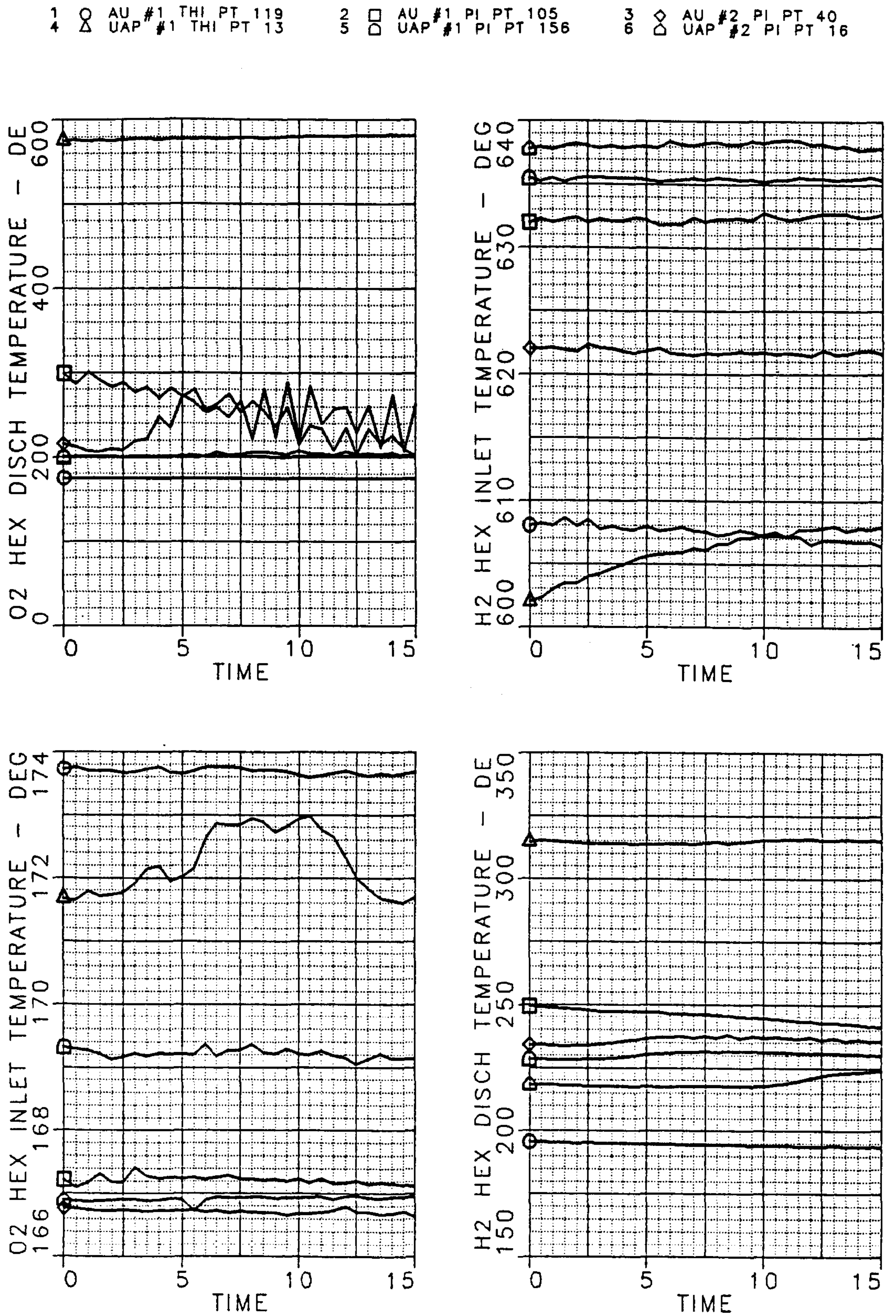


03/02/87
RBK

Figure 13

6208C

PRATT & WHITNEY - ROCKET PERFORMANCE



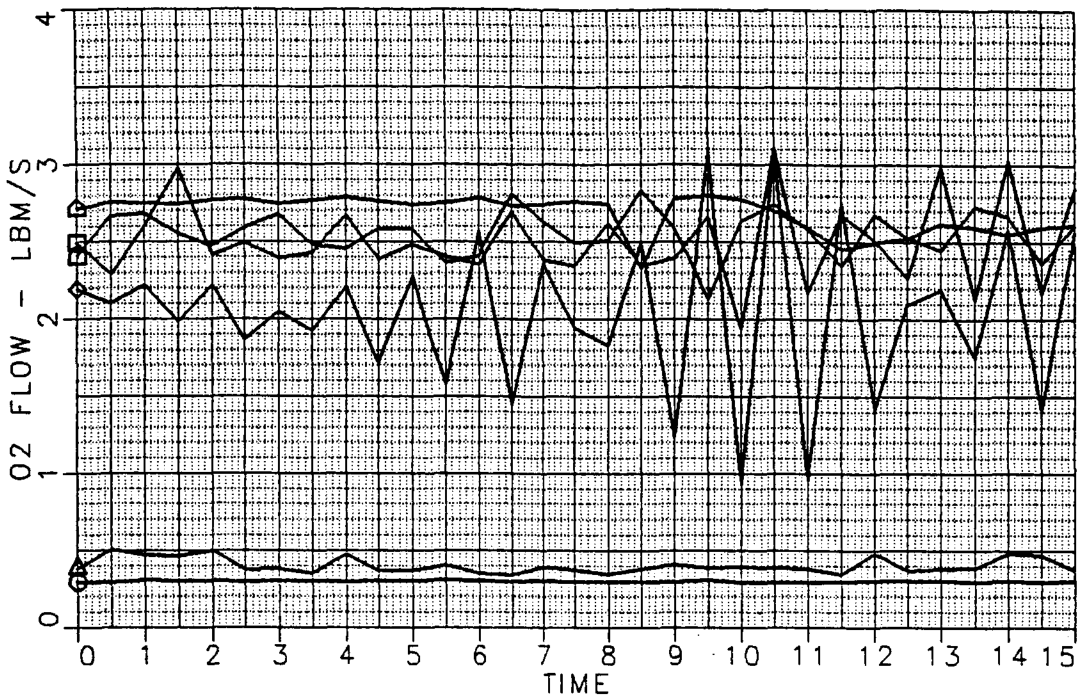
03/02/87
RBK

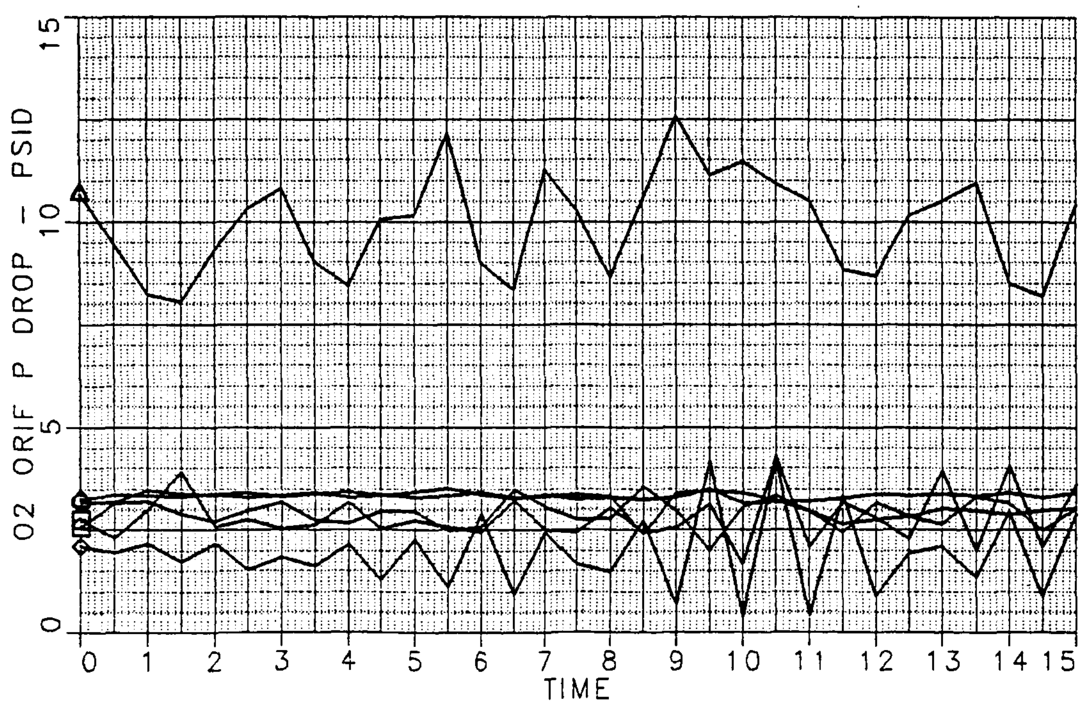
Figure 14

6208C

PRATT & WHITNEY - ROCKET PERFORMANCE

1 ○ AU #1 THI PT 119   2 □ AU #1 PI PT 105   3 ◇ AU #2 PI PT 40
4 △ UAP #1 THI PT 13   5 □ UAP #1 PI PT 156   6 △ UAP #2 PI PT 16





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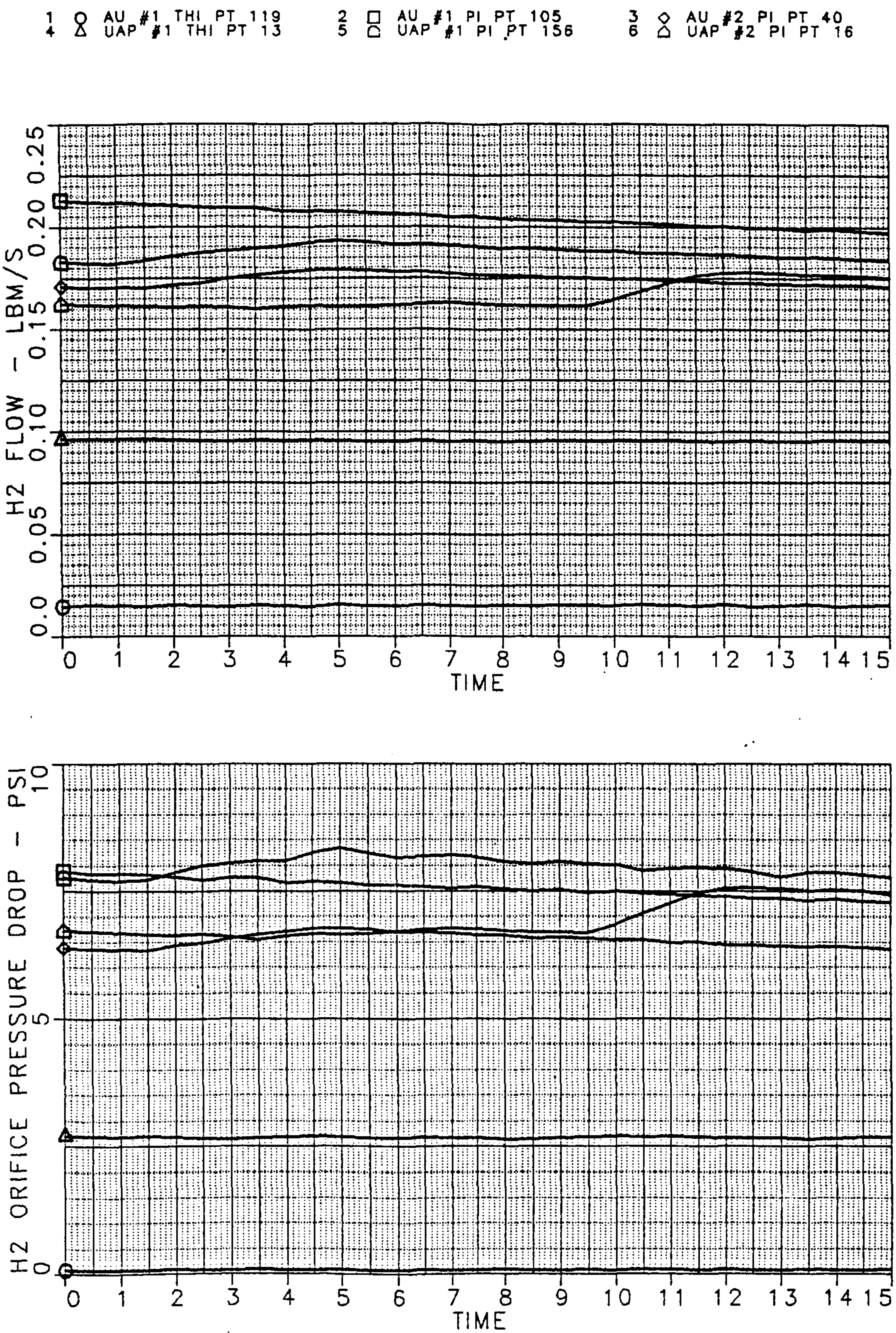
RBK

Figure 15

6208C

PRATT & WHITNEY - ROCKET PERFORMANCE

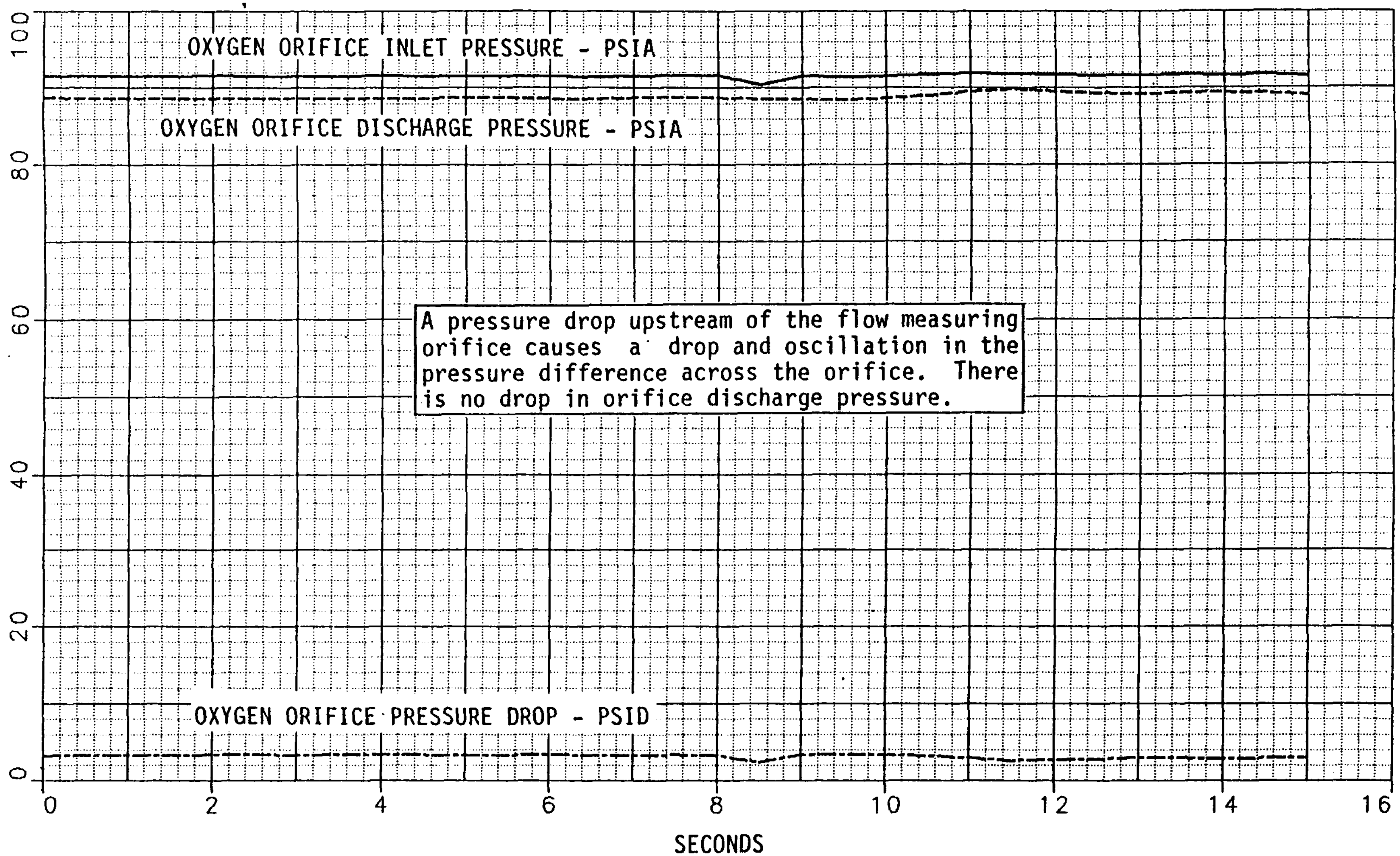


03/02/87
RBK

Figure 16

6206C

PRATT & WHITNEY
UAP #2, PI, TEST POINT 16



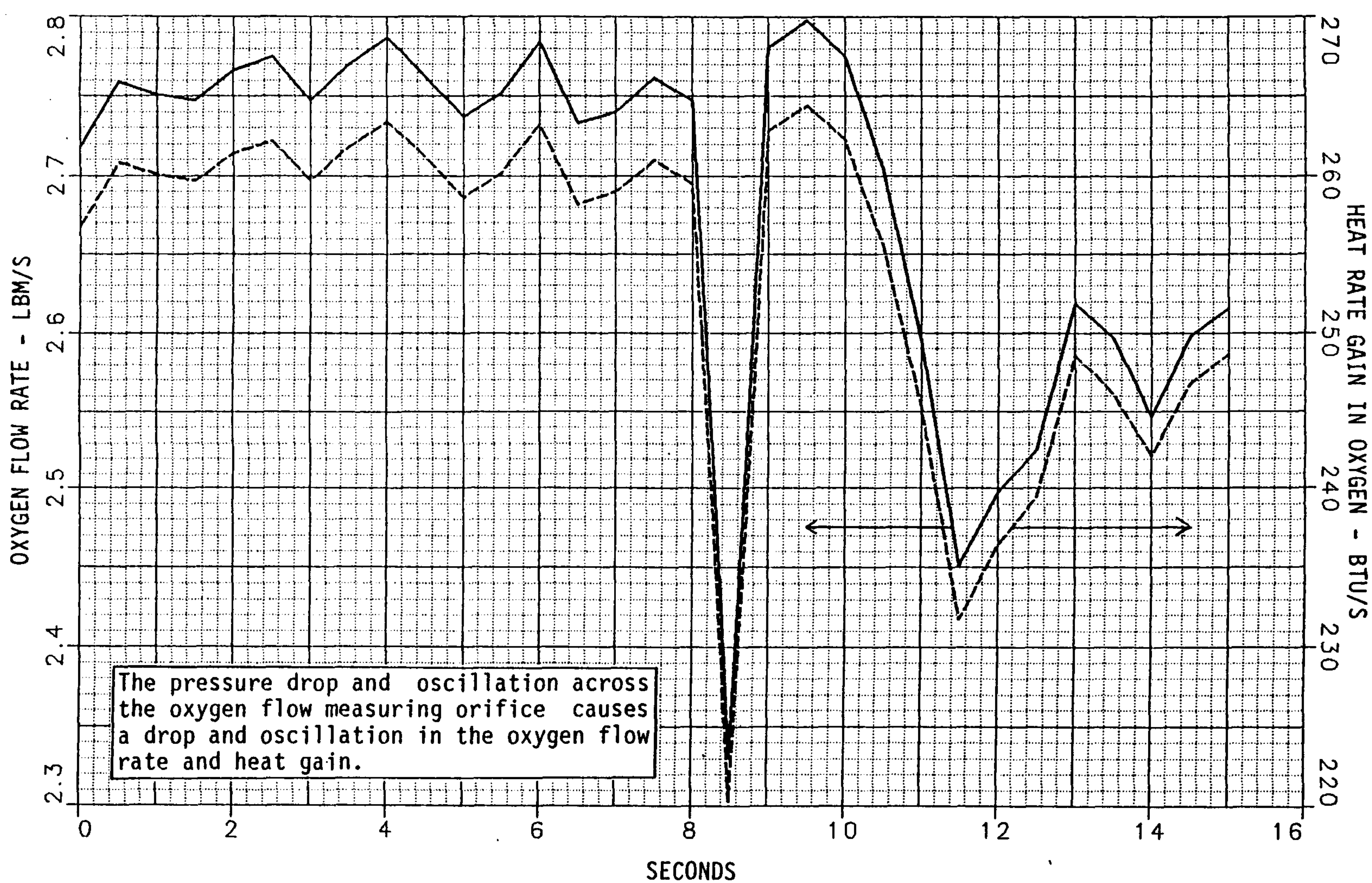
01/14/87
KALDOR,RAY

Figure 17

6208C

PRATT & WHITNEY

UAP #2, PI, TEST POINT 16



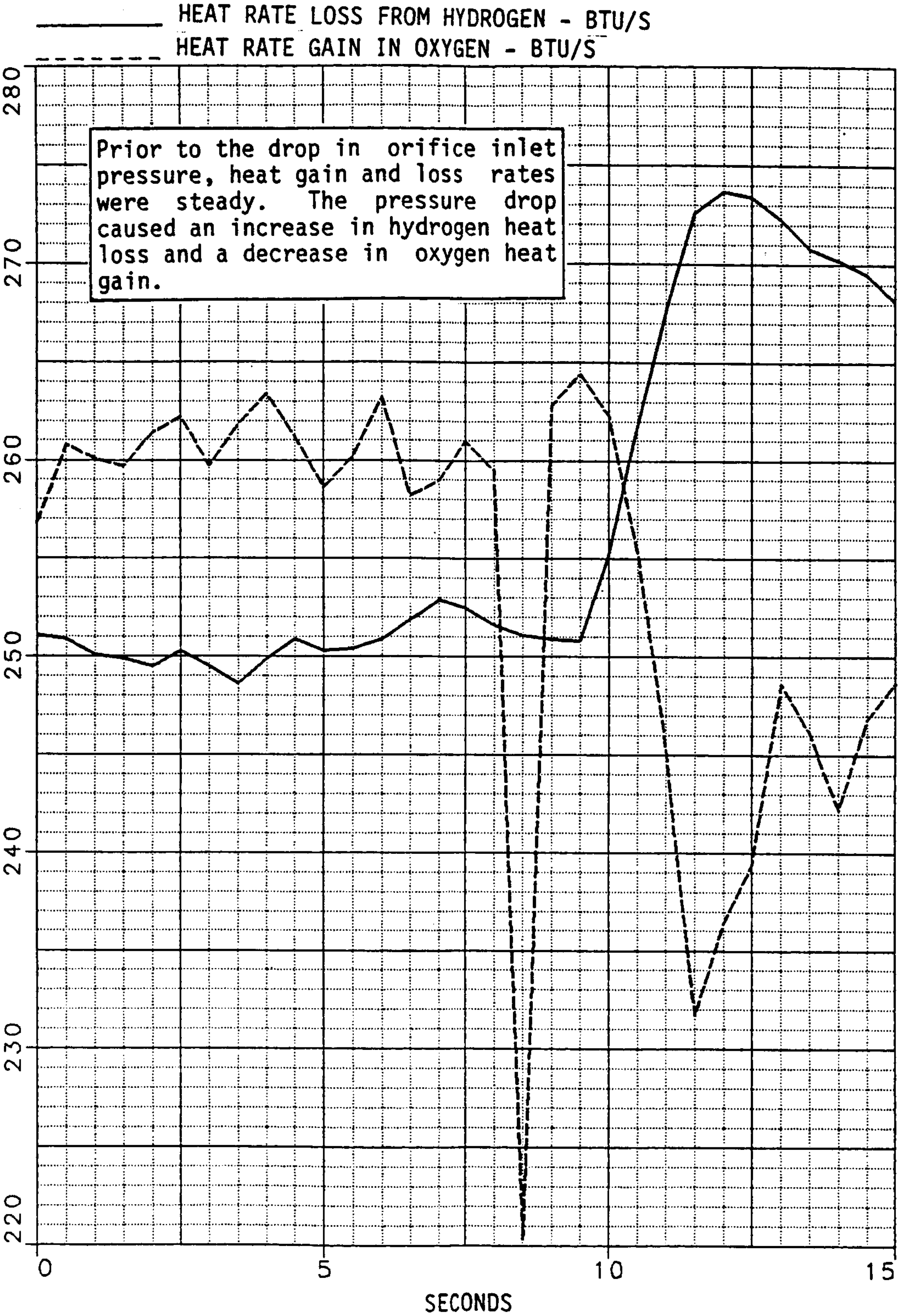
01/14/87
KALDOR,RAY

Figure 18

6208C

PRATT & WHITNEY

UAP #2, PI, TEST POINT 16



01/14/87
KALDOR, RAY

Figure 19

6208C

APPPENDIX C

Internal Correspondence

UNITED TECHNOLOGIES PRATT&WHITNEY

Engineering Division

To: P. Kanic
From: Luis J. Lago
Subject: Evaluation And Comparison Of The Alpha United, Inc. And United Aircraft Product, Inc. Heat Exchangers For The R10-IIB Engine
Date: March 16, 1987
cc: J. Black, R. Peckham, J. Rannie, File

HIGHLIGHTS

- Both heat exchanger test results reveal that the oxygen is vaporized with a quality greater than 95%, for all those cases presented in Table A1 and A2.
- At inverted orientation, neither heat exchangers satisfied the allowable oxygen flow oscillations described in the preliminary purchase performance specifications F-645 (see Table A1 and A2).
- At normal orientation: The Alpha United Heat Exchanger exceeded the maximum allowable pressure drop in the hydrogen circuit at pumped idle and at tank head idle when the hydrogen is at full flow (see Table A1). The United Aircraft Product Heat Exchanger exceeded the maximum allowable pressure drop in the oxygen circuit at pumped idle (see Table A2).
- The best design is the Alpha United Heat Exchanger. This recommendation is based on a better oxygen flow stability, less weight and smaller sizes (see Table A1, A2 and Figures A1 and A2).
- Final selection will be made by the Performance Group. They have to determine if these results are acceptable with the engine performance.

DETAILS

The RL10-IIB multi-mode low thrust engine incorporates a heat exchanger in the engine cycle. The purpose of the heat exchanger in the engine cycle is to vaporize liquid oxygen using energy available from gaseous hydrogen in a stable manner prior to injection into the thrust chamber. Injection of gaseous oxygen provides more efficient combustion and stable engine operation during Tank Head Idle and Pumped Idle operation.

Two individual vendor designs were tested to determine the performance of each. One design was created and fabricated by United Aircraft Products, Inc., and incorporates a low heat transfer approach. The other concept utilizes a high heat transfer core with an integral damping volume, and was designed and fabricated by Alpha United, Inc. These designs are intended to meet the requirements of Preliminary Purchase Performance Specification (PPS) F-654. These heat exchangers were designed primarily to operate in the following two modes. Tank Head Idle (THI) which allows the engine to operate at 1-2% of rated thrust to provide propellant settling and efficient engine thermal conditioning; Pumped Idle (PI) which is 10-25% of rated thrust to provide tank pressurization is in preparation for rated thrust operation and can be used for maneuver thrust or low -g payload delivery. The Oxidizer Heat Exchanger (OHE) is also used to provide gaseous oxidizer for tank pressurization during rated thrust operation, however, the only impact on design is higher operating pressure.

The main purpose of these tests were to demonstrate the performance of each heat exchanger designs as specified by PPS F-654. Each heat exchanger is designed primarily to operate in THI and PI modes. An inversion test was included to determine the effects of gravity on OHE performance. Two units of each design were run to demonstrate unit-to-unit repeatability; therefore, a total of four units were tested.

The Alpha United Heat Exchanger (AU HEX.) performance test data, for units #1 and #2, are presented in Tables B1 to B4. The oxygen heat pick-up, pressure oscillation and delta pressure vs oxygen flow rate curves are presented in Graphs B1 to B4 for Unit #1 and Graphs B5 to B8 for Unit #2. The design points and test results are presented in Table A1.

The United Aircraft Product Heat Exchanger (UAP HEX.) performance test data, for unit #1 and #2, are presented in Tables C1 to C4. The oxygen heat pick-up, pressure oscillation and delta pressure vs oxygen flow rate curves are presented in Graphs C1 to C4 for Unit #1 and Graphs C5 to C8 for Unit #2. The design points and test results are presented in Table A2.

The heat exchanger must gasify the oxygen requirements at low thrust conditions specified herein without exceeding the maximum flow oscillation or maximum flow instability described in the PPS F-654. The oxygen flow oscillation ΔW is calculated as follows:

$$\Delta P_{MAX} = \frac{(W_{MAX})^2 * K}{A^2 * \rho}; \qquad W_{MAX} = \sqrt{\frac{A^2 * \rho}{K}} * \sqrt{\Delta P_{MAX}} = C * \sqrt{\Delta P_{MAX}}$$

$$\Delta P_{MIN} = \frac{(W_{MIN})^2 * K}{A^2 * \rho}; \qquad W_{MIN} = \sqrt{\frac{A^2 * \rho}{K}} * \sqrt{\Delta P_{MIN}} = C * \sqrt{\Delta P_{MIN}}$$

Assuming: A, K and ρ constant for Max. and Min. conditions.

$$W_{MAX} - W_{MIN} = C * \left[\sqrt{\Delta P_{MAX}} - \sqrt{\Delta P_{MIN}}\right]$$

$$\Delta W = \frac{W_{MAX} - W_{MIN}}{2}$$

The reason of having a maximum oxygen flow oscillation or maximum oxygen flow instability in the PPS F-654 is because the lower the flow oscillation, the more uniform is the combustion of the fuel and this imply a better control of the engine thrust.

Analyzing the oxygen flow stabilities by looking at the flow oscillation data, on Table A1 and A2:

At PI mode, normal orientation, UAP HEX is 0.045 Lbm/sec more stable than AU HEX. and both are within the specifications (see Table A1 and A2).

At PI mode, inverted orientation, no data available.

At THI mode, normal orientation, AU HEX. is 0.009 Lbm/sec more stable than UAP HEX. and both are within the specifications (see Table A1 and A2).

At THI mode, inverted orientation, AU HEX. is more stable than UAP HEX. and AU HEX. is 0.223 Lbm/sec over the specifications (see Table A1 and A2).

At THI mode, normal orientation, hydrogen at full flow for AU HEX., the AU HEX. is 0.001 Lbm/sec more stable than UAP HEX. and both are within the specifications (see Table A1 and A2).

At THI mode, inverted orientation, hydrogen at full flow for AU HEX, AU HEX. is more stable than UAP HEX and AU HEX is 0.189 Lbm/sec over the specifications (see Table A1 and A2).

Analyzing the pressure drop from the hydrogen and oxygen circuits, on Tables A1 and A2:

At PI mode, normal orientation; A) In the hydrogen circuit, AU HEX is 1.60 PSI over the specification and UAP HEX is within the specifications. B) In the oxygen circuit, AU HEX is 6.20 PSI over and UAP HEX is 2.29 PSI over the specifications.

At PI mode, inverted orientation, no data available.

At THI mode, normal and inverted orientations; both circuits, on both heat exchangers are within the specifications.

At THI mode, normal orientation; hydrogen at full flow for AU HEX: A) In the hydrogen circuit, AU HEX is 0.7 PSI over and UAP HEX is within the specifications. B) In the oxygen circuit, AU HEX and UAP HEX are within the specifications.

At THI mode, inverted orientation; hydrogen at full flow for AU HEX; both circuits, on both heat exchanger are within the specifications.

Luis Jorge Lago.
L. J. Lago

J. Black
Approved by: J. Black

LJL/ec
Attachments

TABLE - A1

RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.

DESIGN POINTS AND TEST DATA

	PPS	AU, INC.	TEST RESULTS PI		PPS	AU, INC.	TEST RESULTS THI (H_2 BYPASS)		TEST RESULTS THI (H_2 FULL FLOW)	
	F-654 P.I. DESIGN POINTS	P.I. DESIGN POINTS	UNIT #1 NORMAL ORIENTA-TION	UNIT #2 NORMAL ORIENTA-TION	F-654 THI DESIGN POINTS	THI DESIGN POINTS	UNIT #1 NORMAL ORIENTA-TION	UNIT #2 INVERTED ORIENTA-TION	UNIT #1 NORMAL ORIENTA-TION	UNIT #2 INVERTED ORIENTA-TION
HEAT LOAD (BTU/SEC)	-	309.93	267.6	260.6	-	42.04	39.50	34.0	48.1	54.0
- HYDROGEN CIRCUIT -										
Flow Rate (LBM/SEC)	0.190	0.190	0.200	0.194	0.094	0.024	0.032	0.032	0.102	0.098
Inlet Temperature (R)	659.0	659.0	633.3	621.1	594.0	606.6	606.6	602.4	599.6	598.7
Inlet Pressure (PSIA)	46.7	46.7	32.79	26.30	9.0	9.00	15.90	15.62	24.3	21.5
Outlet Temperature (R)	-	209.0	273.8	225.0	-	167.9	251.3	262.6	467.1	444.9
Outlet Pressure (PSIA)	-	44.6	28.22	22.87	-	8.60	15.45	15.38	21.5	19.5
Pressure Drop (PSID)	2.40(MAX)	2.10	4.57	3.43	2.10(MAX)	0.40	0.45	0.24	2.8	2.0
- OXYGEN CIRCUIT -										
Flow Rate (LBM/SEC)	2.84	2.84	2.84	2.84	0.310	0.310	0.310	0.310	0.305	0.504
Inlet Temperature (R)	168.0	168.0	168.7	166.4	165.8	165.8	174.5	175.0	173.4	174.2
Inlet Pressure (PSIA)	110.0	110.0	87.01	86.2	20.0	20.00	30.00	33.48	26.8	33.0
Outlet Temperature (R)	-	256.0	200.0	197.2	-	311.0	350.0	270.0	482.0	256.4
Outlet Pressure (PSIA)	-	105.7	75.01	76.40	-	19.12	29.30	33.30	26.4	32.2
Pressure Drop (PSID)	4.70(MAX)	4.30	12.00	9.80	2.30(MAX)	0.88	0.70	0.18	0.4	0.8
Discharge Quality	95% (MIN)	100%	100%	97%	95% (MIN)	100%	100%	100%	100%	100%
Allowable Flow Oscil-lation (LBM/SEC)	0.20(MAX)		0.193	0.191	0.050(MAX)		0.006	0.273	0.014	0.239
Allowable Pressure Oscil-lation (PSI)			0.490	0.480			0.130	1.260	0.323	0.787

1 FOLDOUT FRAME

2 FOLDOUT FRAME

TABLE - A2

RL10 GOX HEAT EXCHANGER

UNITED AIRCRAFT PRODUCT, INC.

DESIGN POINTS AND TEST DATA

	(PPS) F-654 P.I. DESIGN POINTS	UAP, INC P.I. DESIGN POINTS	TEST RESULTS PI UNIT #1 NORMAL ORIENTATION	TEST RESULTS PI UNIT #2 NORMAL ORIENTATION	PPS F-654 THI DESIGN POINTS	UAP, INC THI DESIGN POINTS	TEST RESULTS THI UNIT #1 NORMAL ORIENTATION	TEST RESULTS THI UNIT #2 INVERTED ORIENTATION
HEAT LOAD (BTU/SEC)		269.27	283.3	277.8		56.95	47.35	19.10
- HYDROGEN CIRCUIT -								
Flow Rate (LBM/SEC)	0.190	0.190	0.195	0.193	0.094	0.094	0.104	0.112
Inlet Temperature (R)	659.0	659.0	637.0	637.4	594.0	594.0	601.9	600.8
Inlet Pressure (PSIA)	46.7	46.70	26.60	24.60	9.0	9.00	21.00	24.3
Outlet Temperature (R)		232.0	244.8	232.20		416.0	464.7	552.5
Outlet Pressure (PSIA)		45.44	24.70	23.07		6.97	19.76	23.07
Pressure Drop (PSID)	2.409(MAX)	1.26	1.90	1.53	2.10(MAX)	2.03	1.24	1.23
- OXYGEN CIRCUIT								
Flow Rate (LBM/SEC)	2.84	2.84	2.84	2.84	0.310	0.310	0.310	0.202
Inlet Temperature (R)	168.0	168.0	167.8	167.0	165.8	165.8	175.4	174.8
Inlet Pressure (PSIA)	110.0	110.0	87.60	86.0	20.0	20.00	30.11	28.10
Outlet Temperature (R)		206.0	202.8	213.0		589.0	465.0	600.3
Outlet Pressure (PSIA)		105.6	81.10	78.53		19.50	29.15	27.83
Pressure Drop (PSID)	4.70(MAX)	4.40	6.50	7.47	2.30(MAX)	0.50	0.96	0.27
Discharge Quality	95% (MIN)	100%	100%	100%	95% (MIN)	100%	100%	100%
Allowable Flow Oscillation (LBM/SEC)	0.20(MAX)		0.136	0.159	0.050(MAX)		0.015	*
Allowable Pressure Oscillation (PSI)			0.340	0.400			0.350	5.640

* FLOW OSCILLATION IMPOSSIBLE TO CALCULATE. INSTABILITY IS TOO HIGH

1 FOLDOUT FRAME

2 FOLDOUT FRAME

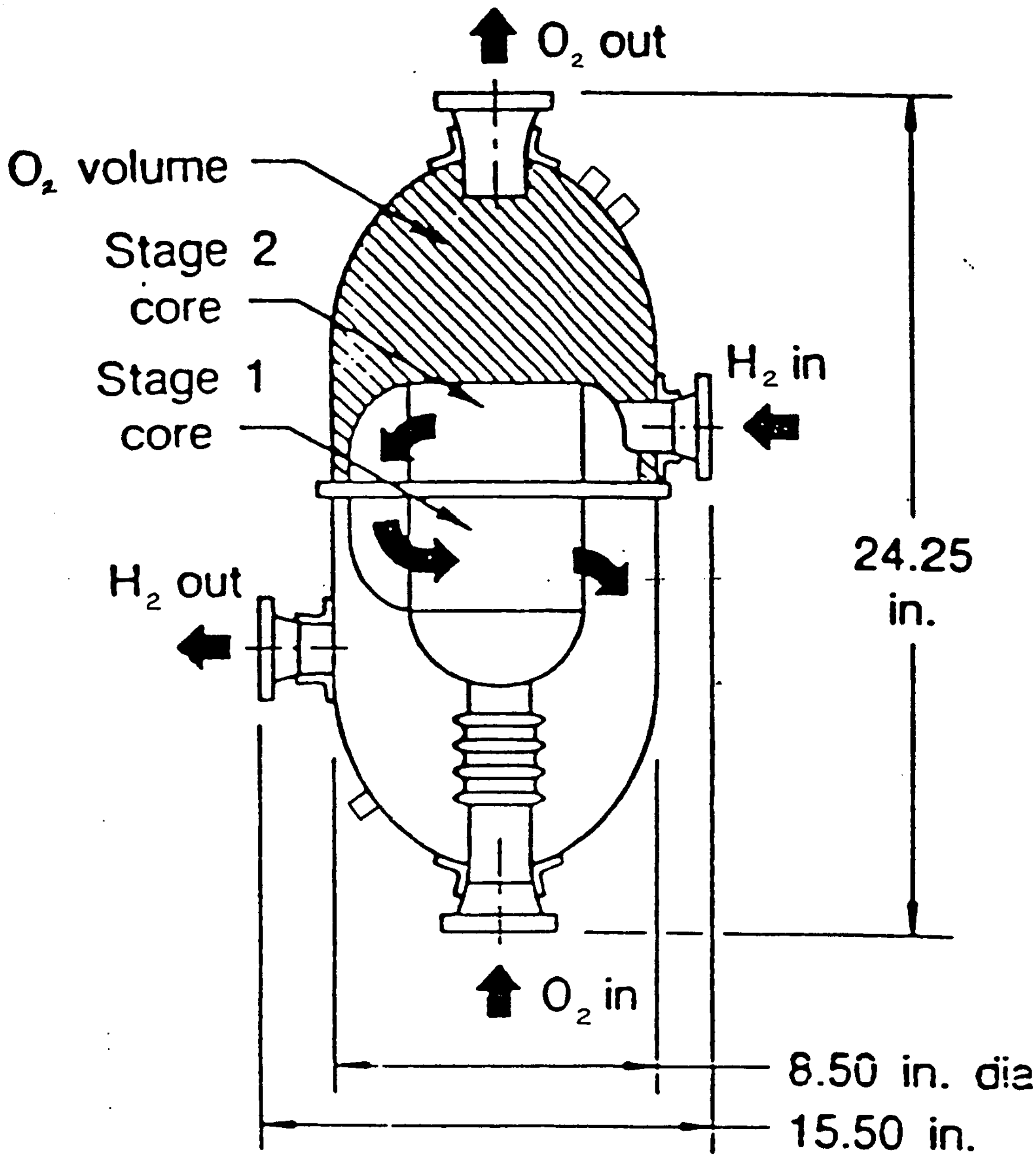


FIGURE A1. HIGH HEAT TRANSFER (AU) OHE
(WEIGHT ≈ 30 lbs.)

TABLE B1

RL10 GOX HEAT EXCHANGER
ALPHA UNITED, INC.
PERFORMANCE TEST DATA
(HYDROGEN CIRCUIT)
- UNIT #1 -

TEST POINT	T Hin (R)	P Hin (psia)	T Hout (R)	P Hout (psia)	ΔP (psi)	Q (Btu/s)	Flow Rate (lbm/s)
(PUMPED IDLE - NORMAL ORIENTATION)							
90. *	638.8	43.2	593.2	37.6	5.6	20.8	0.198
91. *	635.5	42.1	581.5	36.7	5.4	35.7	0.194
92. *	633.0	42.1	572.4	36.6	5.5	41.2	0.196
93. *	632.5	42.2	567.1	36.7	5.5	44.7	0.197
94. *	632.8	42.2	558.1	36.7	5.6	52.1	0.199
95. *	633.7	40.8	537.6	35.5	5.3	66.7	0.194
96. *	634.4	38.8	513.3	33.8	5.0	79.1	0.187
97. *	635.5	38.4	461.7	33.5	4.9	120.7	0.194
98.	635.2	33.7	294.6	29.3	4.4	245.8	0.197
99.	635.3	30.8	233.9	26.6	4.2	286.7	0.194
100.	627.6	37.2	348.1	32.5	4.7	209.5	0.206
101.	628.6	38.5	447.5	33.5	5.0	126.9	0.197
102.	628.8	32.2	233.8	27.6	4.6	302.2	0.207
103.	629.4	35.0	335.3	30.1	4.9	218.0	0.203
104.	630.5	35.3	333.2	30.5	4.8	220.7	0.204
105.	632.5	31.4	242.8	26.9	4.5	288.0 ▲	0.200
106.	633.3	32.1	245.1	27.4	4.7	294.8 ▲	0.206
107.	638.9	29.7	227.1	25.4	4.3	294.1	0.193
108.	641.7	30.5	244.3	25.9	4.6	278.9 ▲	0.193
(TANK HEAD IDLE - NORMAL ORIENTATION)							
111.	599.6	24.3	565.7	21.5	2.8	12.3 ▲	0.102
112.	597.1	35.9	579.5	30.9	5.0	10.8 ▲	0.172
113.	-----	----	-----	-----	---	----	-----
114.	----	----	-----	-----	---	----	-----
115.	610.2	16.0	421.4	15.5	0.5	23.1	0.034
116.	599.1	40.5	562.0	34.6	5.9	26.7	0.202
117.	603.3	41.1	578.8	35.0	6.1	17.8	0.202
118.	602.9	15.8	428.8	15.4	0.4	15.9	0.030
119.	606.9	14.8	194.0	14.8	0.0	22.9	0.015
120.	597.5	14.8	188.8	14.8	0.0	22.7	0.015

* - Unstable boiling

▲ - Disagreement between oxygen and hydrogen heat load, the heat load from hydrogen was used to generate graphs

6208C

TABLE B2

RL-10 GOX HEAT EXCHANGER
ALPHA UNITED, INC.
PERFORMANCE TEST DATA
(OXIDIZER CIRCUIT)
- UNIT #1 -

TEST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	ΔP (psi)	Q (Btu/s)	Flow Rate (lbm/s)	Exit Quality	Pressure Oscillation (psi)
(PUMPED IDLE - NORMAL ORIENTATION)									
90. *	168.0	91.6	439.0	92.1	-0.5	20.8	0.139 ***	VAPOR	+/- 9.813 PSI
91. *	169.0	89.8	411.6	89.2	0.6	35.7	0.249 ***	"	+/-13.709 PSI
92. *	170.0	89.9	394.9	89.9	0.0	41.2	0.295 ***	"	+/-11.955 PSI
93. *	171.0	90.3	381.0	90.1	0.2	44.7	0.323 ***	"	+/-12.284 PSI
94. *	171.0	89.0	362.2	88.8	0.2	52.1	0.394 ***	"	+/-12.853 PSI
95. *	171.0	90.3	274.0	90.0	0.3	66.7	0.595 ***	"	+/- 9.840 PSI
96. *	170.0	89.2	232.3	88.2	1.0	79.1	0.775 ***	"	+/-11.143 PSI
97. *	178.7	88.9	201.9	85.1	3.8	120.7	1.278 ***	"	+/- 6.103 PSI
98.	171.8	87.7	245.6	79.1	8.6	245.8	2.322 ***	VAPOR	+/- 8.536 PSI
99.	168.8	85.1	194.0	69.1	16.0	286.7	3.702	80%	+/- 0.510 PSI
100.	171.4	87.4	198.0	79.0	8.4	209.5	2.595	85%	+/- 0.244 PSI
101.	172.3	87.8	200.2	83.6	4.2	126.9	1.374 ***	VAPOR	+/- 4.135 PSI
102.	168.1	85.3	193.9	69.0	16.3	302.2	3.495	91%	+/- 0.484 PSI
103.	170.0	87.6	216.9	79.7	7.9	218.0	2.229 ***	VAPOR	+/-11.023 PSI
104.	169.6	85.9	223.0	78.0	7.9	220.7	2.216 ***	VAPOR	+/- 9.241 PSI
105.	167.2	88.4	220.5	78.9	9.5	288.7 **	2.595	VAPOR	+/- 1.142 PSI
106.	167.2	88.3	250.7	79.6	8.7	262.2 **	2.464	VAPOR	+/- 2.669 PSI
107.	166.3	85.4	194.5	70.4	15.0	294.1 **	3.573	85%	+/- 0.576 PSI
108.	166.9	89.0	278.2	81.5	7.5	250.8 **	2.225	VAPOR	+/- 1.191 PSI
(TANK HEAD IDLE - NORMAL ORIENTATION)									
111.	173.4	26.8	482.0	26.4	0.4	48.1	0.305	VAPOR	+/- 0.323 PSI
112.	174.6	28.8	524.1	28.4	0.4	50.4	0.312	VAPOR	+/- 0.204 PSI
113.	-----	----	-----	----	---	----	-----	-----	---------
114.	-----	----	-----	----	---	----	-----	-----	---------
115.	173.1	28.9	175.9	28.2	0.7	23.1	0.318	81%	+/- 0.113 PSI
116.	173.1	29.2	178.1	28.5	0.7	26.7	0.307	97%	+/- 0.210 PSI
117.	175.4	30.7	397.6	30.2	0.5	28.6	0.207	VAPOR	+/- 0.249 PSI
118.	175.8	30.7	202.5	30.0	0.7	19.6	0.206	VAPOR	+/- 0.259 PSI
119.	173.6	29.2	193.9	28.2	1.0	27.9	0.301	VAPOR	+/- 0.109 PSI
120.	175.4	30.6	178.8	29.8	0.8	20.0	0.222	VAPOR	+/- 0.115 PSI

* - Unstable boiling
** - Q calculated from oxygen test data
*** - Oxygen flow rate calculated from Q calculated from hydrogen test data

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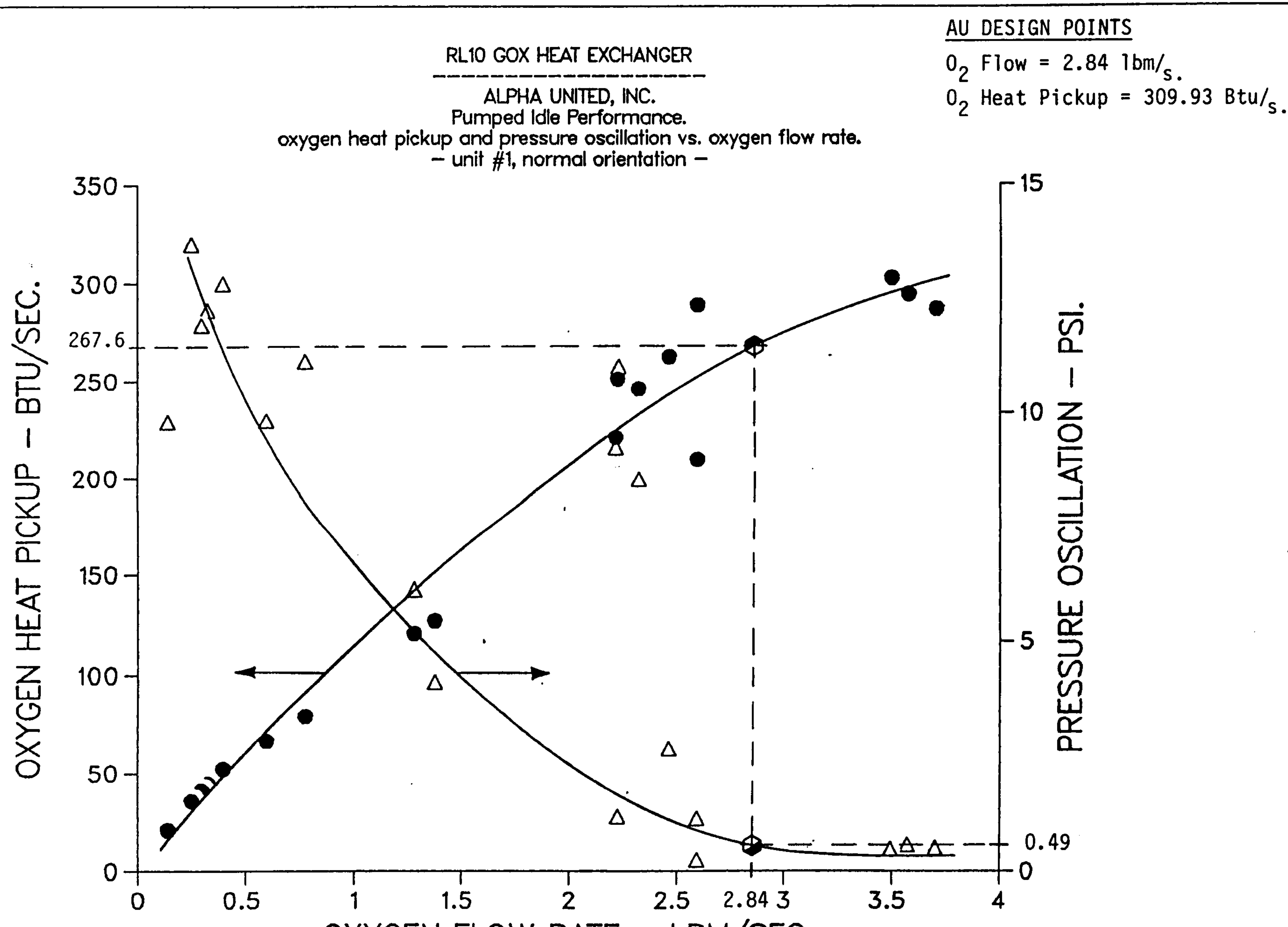

GRAPH - B1.

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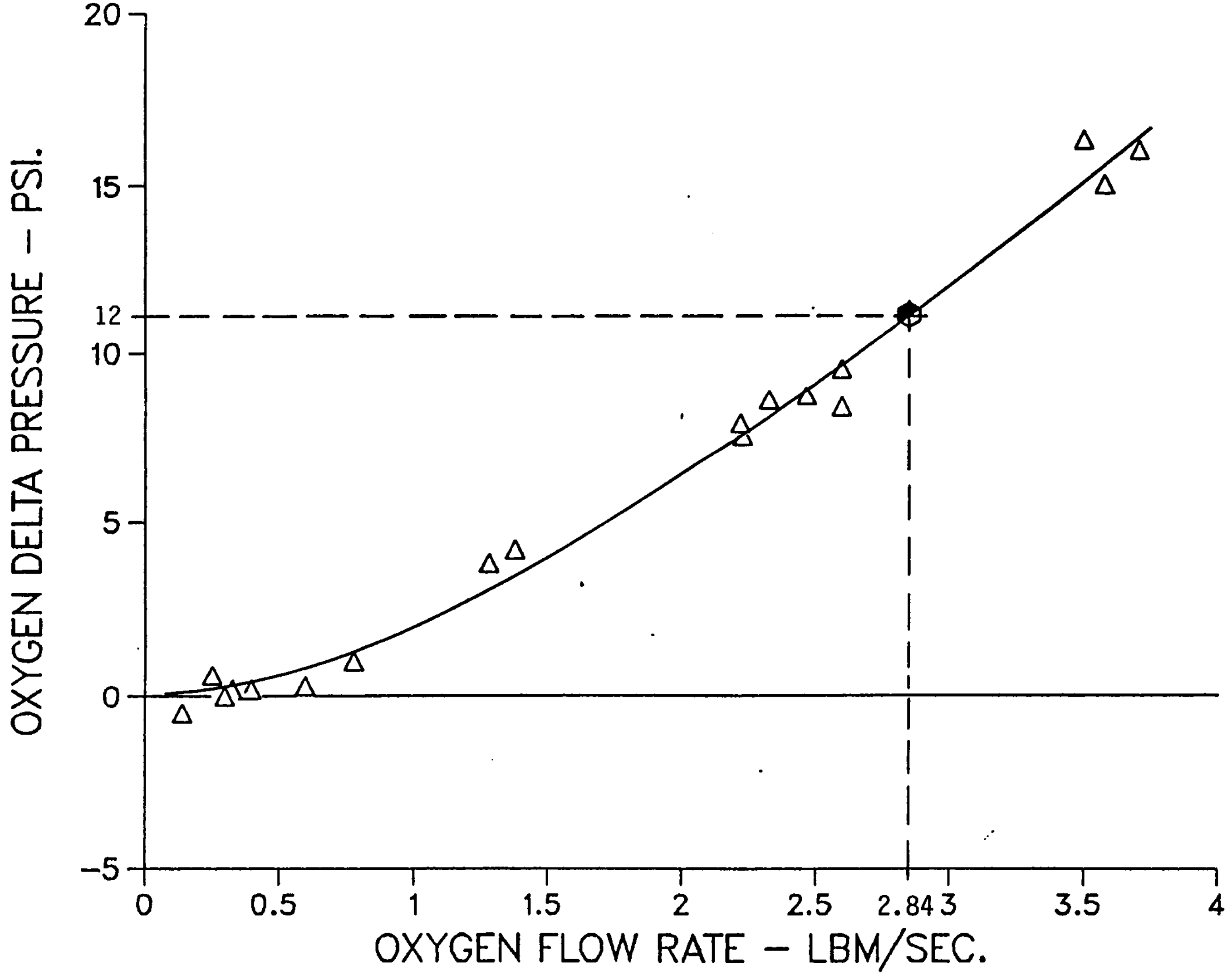
RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.
Pumped Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
— unit #1, normal orientation —

AU DESIGN POINTS

O_2 Flow = 2.84 Lbm/s.
O_2 ΔP = 4.3 psi



GRAPH - B2.

C-2

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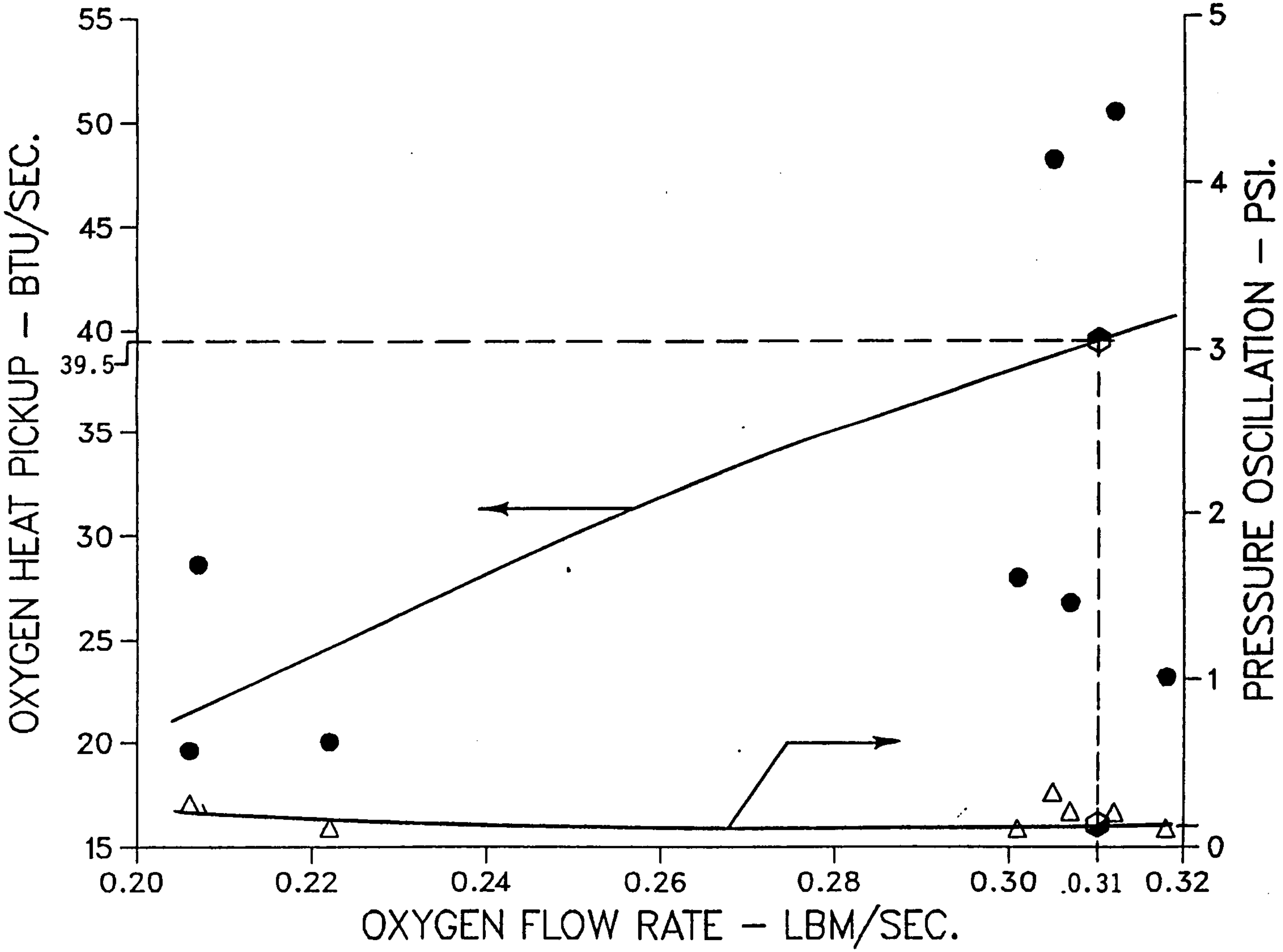
RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.
Tank Head Idle Performance.
oxygen heat pickup and pressure oscillation vs. oxygen flow rate.
– unit #1, normal orientation –

AU DESIGN POINTS

O_2 Flow = 0.31 lbm/s.
O_2 Heat Pickup = 42.04 Btu/s



GRAPH - B3.

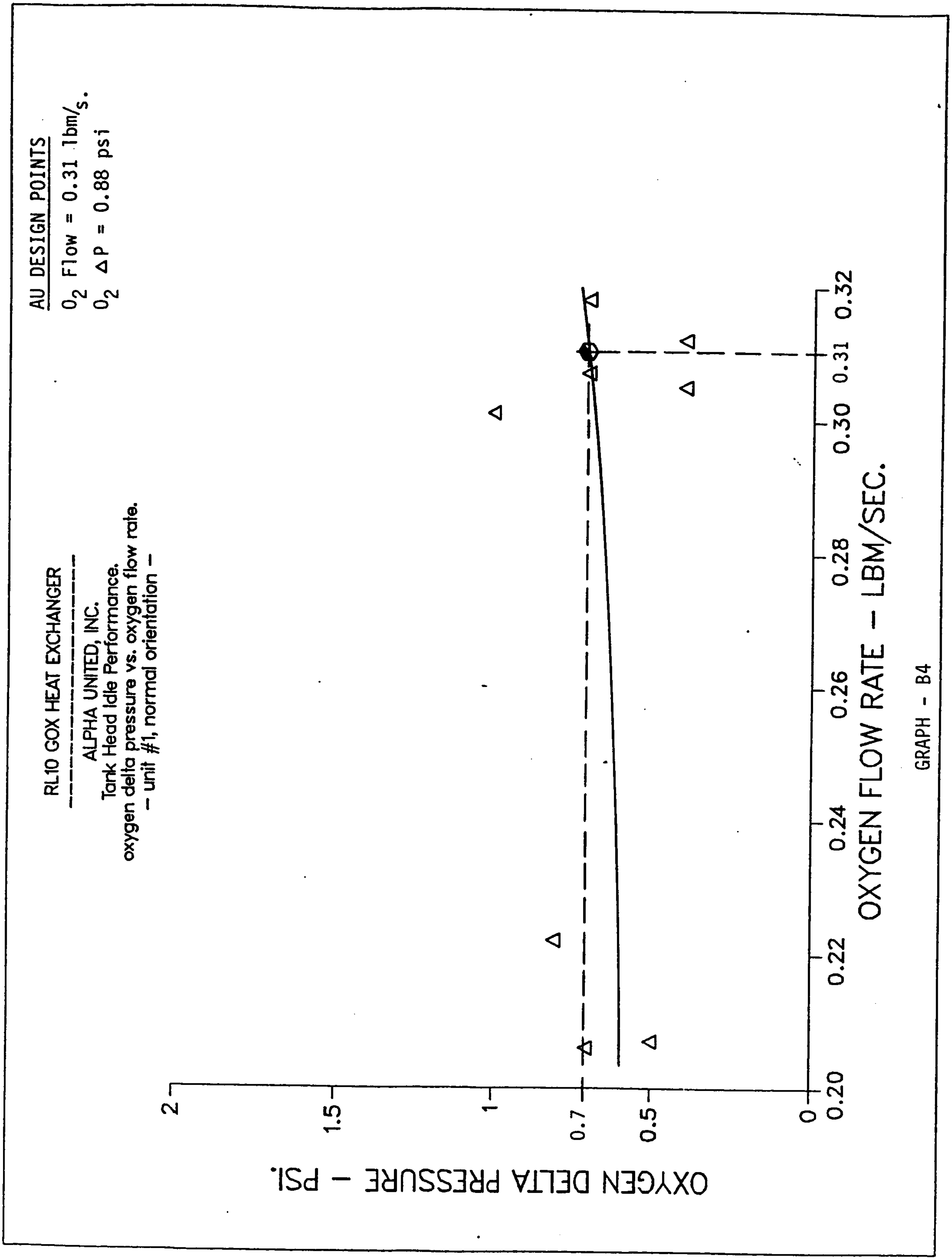

RL10 GOX HEAT EXCHANGER
ALPHA UNITED, INC.
Tank Head Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit #1, normal orientation –
AU DESIGN POINTS
O2 Flow = 0.31 lbm/s.
O2 ΔP = 0.88 psi
OXYGEN DELTA PRESSURE – PSI.
OXYGEN FLOW RATE – LBM/SEC.
0
0.5
0.7
1
1.5
2
0.20
0.22
0.24
0.26
0.28
0.30
0.31
0.32
GRAPH - B4

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TABLE B3

RL-10 GOX HEAT EXCHANGER
ALPHA UNITED, INC.
PERFORMANCE TEST DATA
(HYDROGEN CIRCUIT)
- UNIT #2 -

TEST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	ΔP (psi)	Q (Btu/s)	Flow Rate (lbm/s)
(PUMPED IDLE - NORMAL ORIENTATION)							
30 *	621.4	36.5	610.2	32.3	4.40	7.6	0.189
31 *	521.3	35.3	566.6	31.2	4.10	36.2	0.189
32 *	622.2	34.7	563.6	30.7	4.00	37.9	0.185
33 *	622.3	35.1	556.9	31.0	4.10	43.3	0.189
34 *	622.4	34.8	543.9	30.7	4.10	52.2	0.189
35 *	622.0	33.6	530.9	29.7	3.90	59.0	0.184
36 *	622.3	33.1	496.7	29.3	3.80	82.5	0.186
37 *	622.1	31.9	433.4	28.3	3.60	126.2	0.187
38	622.2	25.8	225.1	22.7	3.10	273.4	0.186
39	621.8	25.0	211.0	22.0	3.00	281.1	0.185
40	621.7	26.2	236.3	22.7	3.50	268.2	0.188
41	621.9	24.8	219.0	21.7	3.10	269.8	0.181
42	634.1	21.8	209.2	19.5	2.30	236.8	0.151
43	678.8	18.7	182.8	17.4	1.30	215.7	0.119
44	619.9	25.3	218.0	22.1	3.20	278.1	0.187
45	612.3	28.8	229.5	24.8	4.00	309.4	0.218
46	629.1	27.2	236.3	23.5	3.70	290.4	0.200
47	619.7	27.4	224.7	23.6	3.80	302.8	0.207
(TANK HEAD IDLE - INVERTED ORIENTATION)							
50 *	596.3	16.8	440.3	16.2	0.60	26.3	0.047
51	605.3	15.9	199.4	15.6	0.30	73.6	0.049
52	600.3	18.1	395.7	17.0	1.10	52.6	0.071
53	598.7	21.5	444.9	19.5	2.00	54.0	0.098
54	600.7	25.2	487.6	22.6	2.60	49.0	0.122
55	600.0	15.1	201.4	15.0	0.10	31.0	0.021
56	599.1	22.0	478.5	20.0	2.00	42.9	0.100
57	605.9	15.3	250.9	15.2	0.10	34.2	0.026
58	604.5	15.0	220.8	14.9	0.10	22.8	0.016
59	605.2	22.4	465.1	20.2	2.20	52.9	0.106
60	606.4	29.7	516.5	26.2	3.50	48.3	0.152

* - Unstable boiling

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TABLE B4

RL-10 GOX HEAT EXCHANGER
ALPHA UNITED, INC.
PERFORMANCE TEST DATA
(OXIDIZER CIRCUIT)
- UNIT #2 -

EST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	P (psi)	Q (Btu/s)	Flow Rate (lbm/s)	Exit Quality	Pressure Oscillation
PUMPED IDLE - NORMAL ORIENTATION)									
30 *	169.0	89.6	559.0	89.4	0.20	7.6	0.043 ***	VAPOR	+/- 8.656
31 *	171.8	87.6	433.2	87.2	0.40	36.2	0.247 ***	"	+/- 6.192
32 *	171.5	86.3	426.3	86.4	0.10	37.9	0.261 ***	"	+/- 5.990
33 *	171.9	89.6	403.1	89.2	0.40	43.3	0.310 ***	"	+/- 7.493
34 *	173.0	86.3	371.8	85.7	0.60	52.2	0.395 ***	"	+/- 7.933
35 *	173.1	89.1	351.0	88.4	0.70	59.0	0.463 ***	"	+/- 6.313
36 *	171.4	85.5	249.8	83.7	1.80	82.5	0.785 ***	"	+/- 8.372
37 *	170.1	87.8	207.5	83.2	4.60	126.2	1.326 ***	VAPOR	+/- 8.324
38	168.01	84.1	194.9	70.9	13.20	273.4	3.326	86%	+/- 1.464
39	166.6	82.8	193.8	67.9	14.90	281.1	3.777	76%	+/- 0.165
40	166.7	87.5	248.8	80.7	6.80	268.1	2.077	VAPOR	+/- 1.900
41	166.3	85.3	196.4	75.0	10.30	269.8	3.000	94%	+/- 0.348
[illegible]	165.9	85.6	197.2	76.9	8.70	236.8	2.879	84%	+/- 0.455
43	165.7	87.1	199.0	81.0	6.10	215.7	2.418	93%	+/- 1.099
44	165.7	85.3	196.3	74.8	10.50	278.1	3.001	98%	+/- 0.527
45	165.8	85.5	196.0	73.9	11.60	309.4	2.911	VAPOR	+/- 0.331
46	165.7	90.4	240.0	82.9	7.50	290.4	2.229	"	+/- 0.378
47	166.0	88.4	197.0	77.1	11.30	302.8	3.078	VAPOR	+/- 0.324
TANK HEAD IDLE - INVERTED ORIENTATION)									
50 *	176.7	31.6	177.5	31.3	0.30	26.3	0.299 ***	VAPOR	+/- 6.752
51	170.3	30.61	174.9	28.9	1.70	73.6	0.808	VAPOR	+/- 2.222
52	176.2	33.2	177.5	32.5	0.70	52.6	0.597	"	+/- 0.883
53	174.2	33.0	177.3	32.2	0.80	54.0	0.504	"	+/- 0.787
54	171.5	33.3	177.7	32.6	0.700	49.0	0.443	VAPOR	+/- 1.018
55	173.2	33.7	178.1	33.5	0.200	31.0	0.364	95%	+/- 0.710
56	177.7	34.3	178.6	33.9	0.400	42.9	0.490 ***	VAPOR	+/- 0.334
57	178.1	34.9	257.8	34.5	0.400	34.2	0.324 ***	"	+/- 1.954
58	178.2	34.7	179.1	34.6	0.100	22.8	0.261 ***	"	+/- 2.211
59	170.6	41.1	182.4	40.8	0.300	52.9	0.410	"	+/- 1.453
60	171.6	41.4	182.8	41.1	0.300	48.3	0.385	VAPOR	+/- 0.800

* - Unstable boiling
*** - Oxygen flow rate calculated from Q calculated from hydrogen test data

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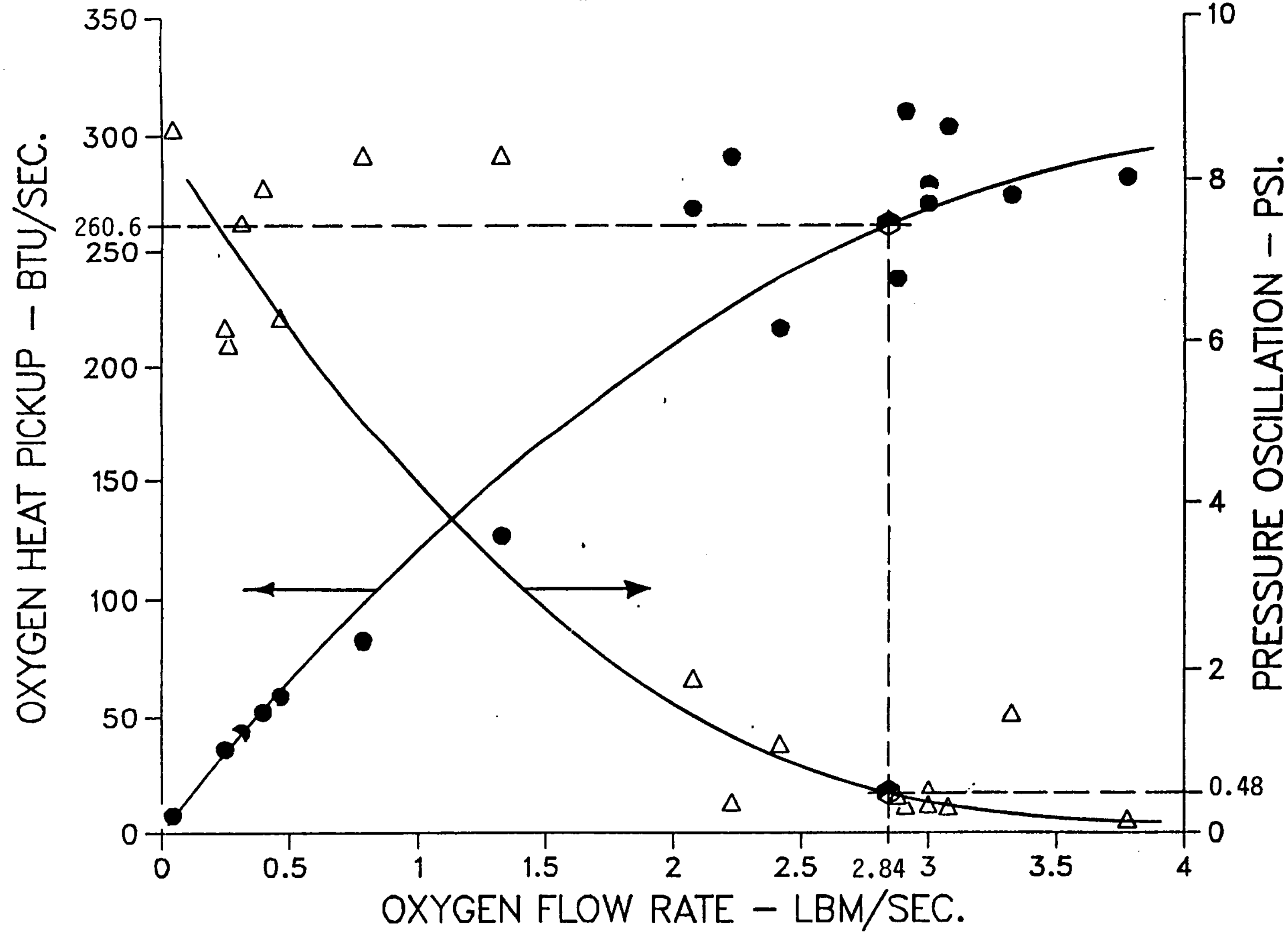
AU DESIGN POINTS

O_2 Flow = 2.84 lbm/s.

O_2 Heat Pickup = 309.93 Btu/s.

RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.
Pumped Idle Performance.
oxygen heat pickup and pressure oscillation vs. oxygen flow rate.
– unit #2, normal orientation –



GRAPH - B5.

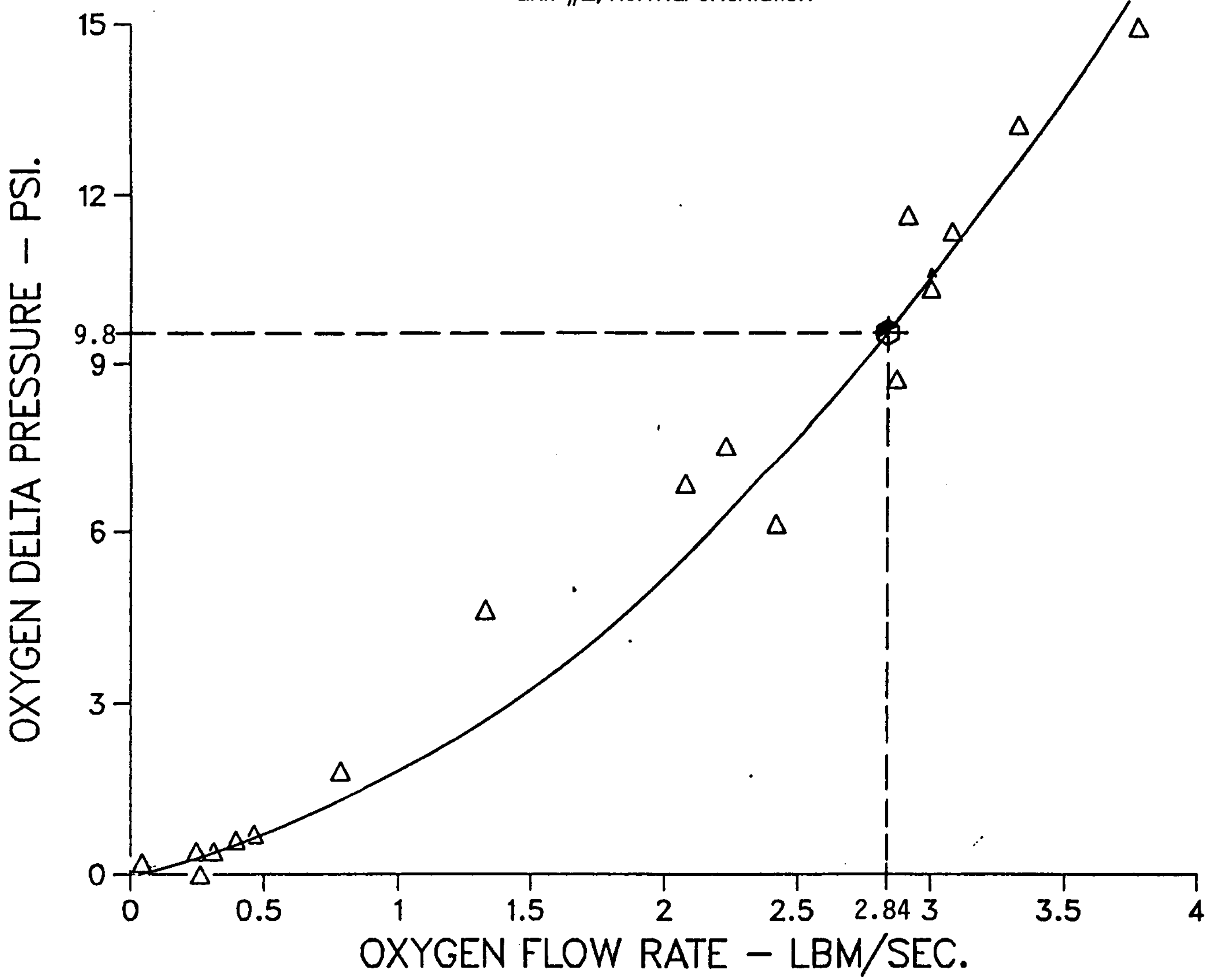
RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.
Pumped Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit #2, normal orientation –

AU DESIGN POINTS

O_2 Flow = 2.84 lbm/s

O_2 ΔP = 4.3 psi



GRAPH - B6.

AU DESIGN POINTS

O_2 Flow = 0.31 lbm/s.

O_2 Heat Pickpu = 42.04 Btu/s.

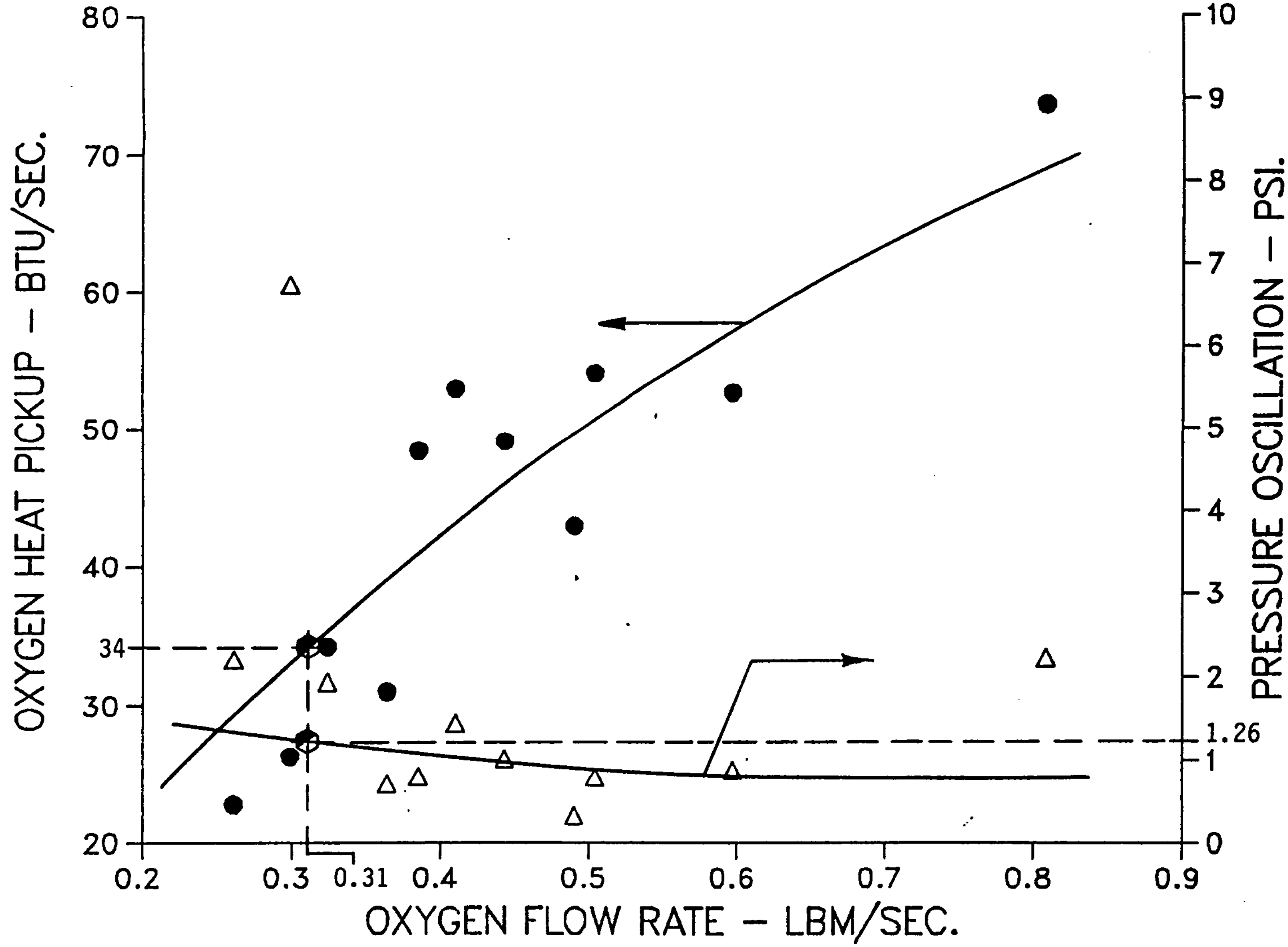
RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.

Tank Head Idle Performance.

oxygen heat pickup and pressure oscillation vs. oxygen flow rate.

– unit #2, inverted orientation –



GRAPH - B7.

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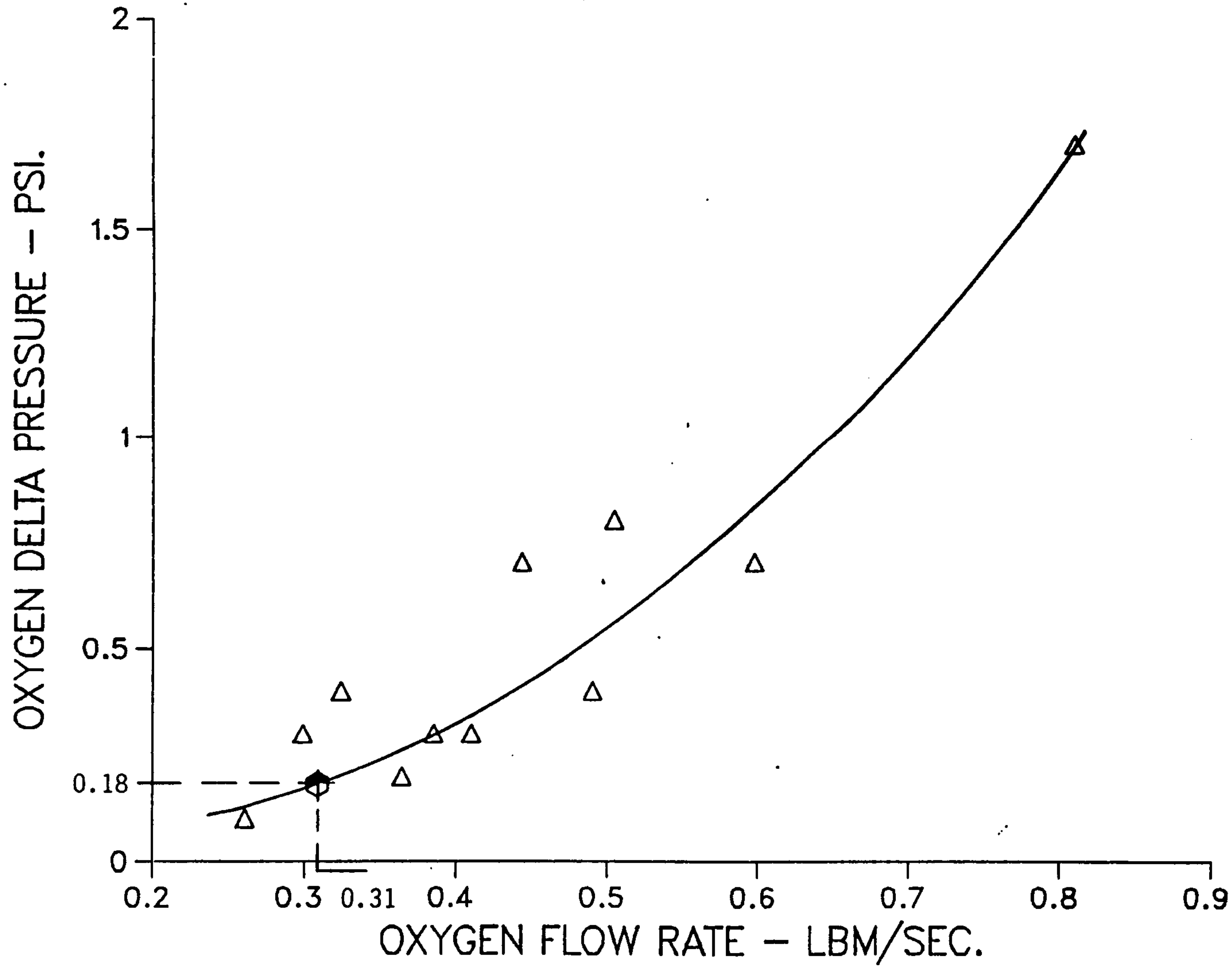
RL10 GOX HEAT EXCHANGER

ALPHA UNITED, INC.
Tank Head Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit #2, inverted orientation –

AU DESIGN POINTS

O_2 Flow = 0.31 lbm/sec

O_2 ΔP = 0.88 psi



GRAPH - B8.

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ALL DIMENSIONS IN INCHES

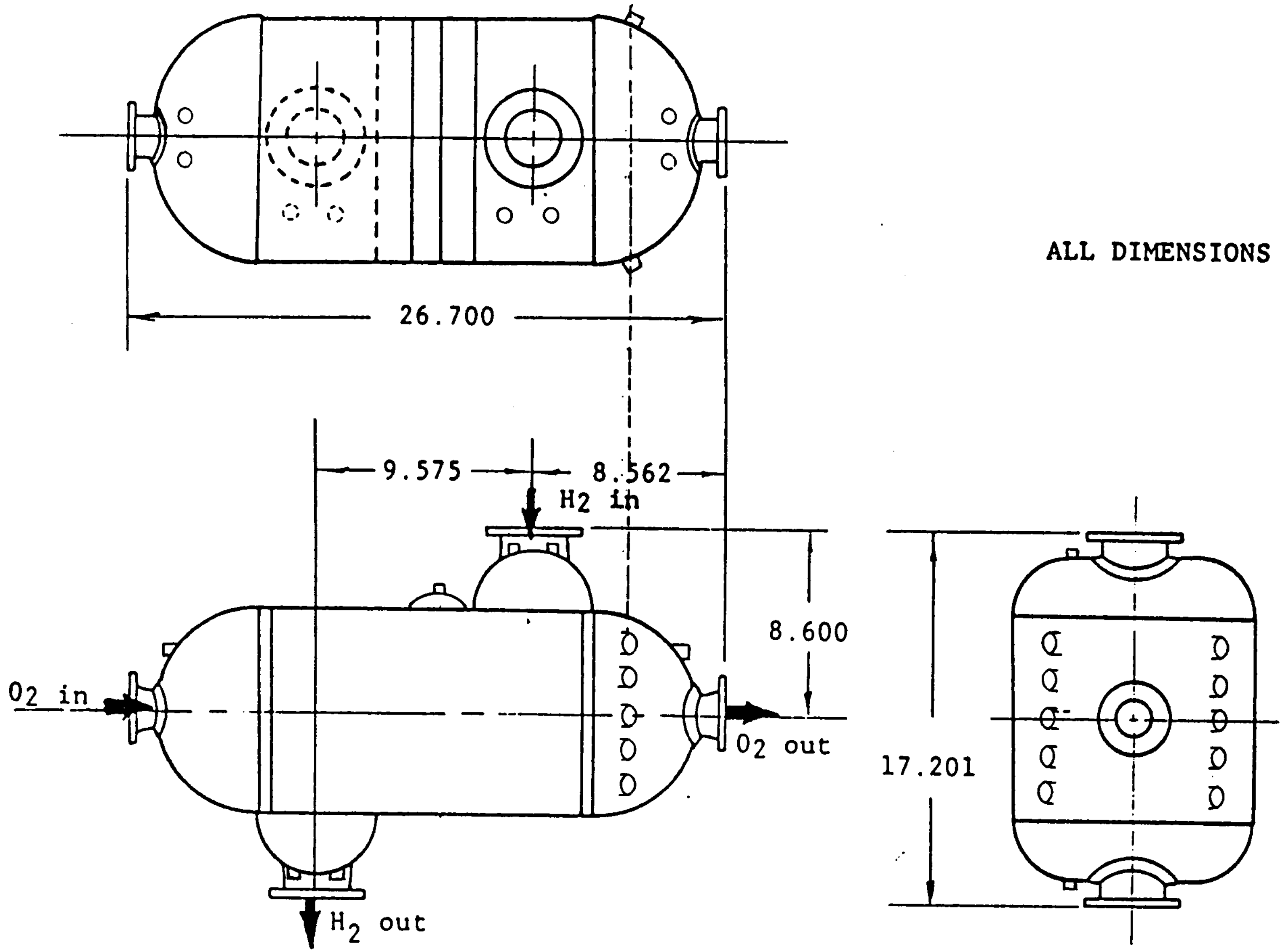

FIGURE A2. LOW HEAT TRANSFER (UAP) OHE
(WEIGHT ≈ 69 lbs.)

TABLE C1

RL10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
PERFORMANCE TEST DATA
(HYDROGEN CIRCUIT)
- UNIT #1 -

TEST POINT	T Hin (R)	P Hin (psia)	T Hout (R)	P Hout (psia)	Q (Btu/s)	Flow Rate (lbm/s)	ΔP (psi)
(TANK HEAD IDLE - NORMAL ORIENTATION)							
130	604.0	15.5	239.2	15.3	42.3	0.042	0.200
131	601.5	17.9	420.0	17.2	33.9	0.074	0.700
132	600.3	21.2	493.7	19.9	45.5	0.103	1.300
133	600.0	23.3	504.2	21.7	43.6	0.121	1.600
134	599.3	21.0	490.0	19.8	26.8	0.101	1.200
135	604.3	21.3	527.6	20.1	27.3 ▲	0.101	1.200
136	601.9	21.0	500.9	19.8	74.9	0.100	1.200
137	598.9	20.1	411.5	19.0	43.2	0.100	1.100
138	607.7	19.2	315.5	18.2	107.3 ▲	0.100	1.000
139	601.7	20.9	474.4	19.6	46.2 ▲	0.102	1.300
(PUMPED IDLE - NORMAL ORIENTATION)							
140 *	634.1	38.2	632.9	35.3	0.8	0.193	2.900
141	634.7	36.3	612.7	33.5	14.4	0.188	2.800
142 *	635.8	36.7	601.3	33.8	23.0	0.191	2.900
143 *	637.1	36.2	587.5	33.4	32.9	0.190	2.800
144 *	637.8	36.4	570.6	33.5	45.7	0.195	2.900
145 *	639.4	35.2	551.6	32.4	58.7	0.191	2.800
146 *	638.8	34.9	515.5	32.0	84.6	0.195	2.900
147 *	638.6	32.5	436.2	29.9	138.5	0.192	2.600
148 *	637.9	27.7	280.9	25.5	248.0	0.189	2.200
149	638.0	24.6	217.1	23.0	285.9	0.184	1.600
150	637.8	25.9	229.9	24.0	292.2	0.194	1.900
151	652.3	21.1	203.6	20.0	241.0	0.146	1.100
152	658.5	18.1	189.3	17.4	178.9	0.104	0.700
153	638.4	25.4	227.8	23.6	288.1	0.190	1.800
154	633.4	28.2	258.0	26.0	288.0	0.208	2.200
155	557.2	25.7	215.6	23.9	254.0	0.199	1.800
156	635.5	25.3	230.7	23.6	278.2	0.186	1.700
157	627.6	29.6	254.7	27.2	305.7	0.222	2.400
158	647.3	21.6	208.5	20.4	240.8	0.149	1.200
159	662.3	18.3	191.9	17.6	182.9	0.106	0.700
160	642.2	25.6	231.1	23.7	288.2	0.190	1.900
161	642.6	27.5	272.9	25.3	295.9	0.195	2.200

* - Unstable boiling

▲ - Disagreement between oxygen and hydrogen heat load, the heat load from hydrogen was used to generate graphs

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TABLE C2.

RL-10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
PERFORMANCE TEST DATA
(OXIDIZER CIRCUIT)
- UNIT #1 -

TEST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	Q (Btu/s)	Flow Rate (lbm/s)	Exit Quality	Pressure Oscillation (psi)	ΔP (psi)
(TANK HEAD IDLE - NORMAL ORIENTATION)									
130	176.4	31.0	578.3	30.2	42.3	0.277	VAPOR	+/- 0.636	0.800
131	176.6	31.3	600.2	30.4	33.9	0.220	"	+/- 0.439	0.900
132	175.7	29.9	601.9	29.1	45.5	0.267	"	+/- 0.112	0.800
133	176.6	31.3	600.8	30.4	43.6	0.283	"	+/- 0.703	0.900
134	175.3	29.2	600.1	28.4	26.8	0.284	"	+/- 0.542	0.800
135	175.9	30.2	602.1	29.7	35.0**	0.210	"	+/- 0.239	0.500
136	176.8	31.4	602.9	30.6	74.9	0.251	"	+/- 0.370	0.800
137	174.4	28.1	596.8	26.6	43.2	0.414	"	+/- 2.222	1.500
138	172.1	27.7	581.3	25.2	74.3**	0.515	"	+/- 1.381	2.500
139	176.1	33.1	602.3	32.0	49.8**	0.305	"	+/- 0.481	1.100
(PUMPED IDLE - NORMAL ORIENTATION)									
140 *	174.0	87.7	540.6	88.0	0.8	0.005 ***	VAPOR	+/- 4.279	-0.300
141	174.0	90.8	631.9	90.7	14.4	0.076 ***	"	+/- 0.119	0.100
142 *	174.0	89.3	634.2	89.4	23.0	0.121 ***	"	+/- 8.298	-0.100
143 *	174.0	90.2	636.1	90.0	32.9	0.173 ***	"	+/- 9.219	0.200
144 *	174.0	90.0	638.1	89.8	45.7	0.239 ***	"	+/-13.767	0.200
145 *	174.0	88.2	639.6	87.7	58.7	0.307 ***	"	+/- 9.002	0.500
146 *	174.0	88.9	636.5	88.1	84.6	0.444 ***	"	+/-13.483	0.800
147 *	174.0	87.8	612.3	85.0	138.5	0.747 ***	"	+/-19.666	2.800
148 *	174.7	82.6	411.1	77.3	248.0	1.766 ***	VAPOR	+/-14.414	5.300
149	166.0	82.8	195.6	71.9	285.9	3.874	75%	+/- 0.238	10.900
150	166.6	87.1	199.6	80.4	292.2	2.537	VAPOR	+/- 0.819	6.700
151	166.5	85.0	197.9	78.1	241.0	3.291	VAPOR	+/- 0.619	6.900
152	166.5	86.3	199.2	81.8	178.9	2.869	VAPOR	+/- 0.266	4.500
153	166.3	86.1	197.7	78.3	288.1	2.928	VAPOR	+/- 0.358	7.800
154	166.8	87.9	276.9	82.1	288.0	2.287	"	+/- 0.498	5.800
155	166.5	86.8	199.0	81.2	254.0	2.696	"	+/- 0.313	5.600
156	169.2	90.5	204.1	84.5	278.2	2.573	"	+/- 0.451	6.000
157	168.4	90.4	209.7	83.3	305.7	2.664	VAPOR	+/- 0.675	7.100
158	168.5	90.0	200.0	84.7	240.8	2.773	92%	+/- 0.325	5.300
159	168.0	89.7	200.2	85.3	182.9	2.845	VAPOR	+/- 0.146	4.400
160	167.9	89.7	199.1	82.5	288.2	2.800	VAPOR	+/- 0.561	7.200
161	174.3	86.9	379.8	82.9	295.9	2.215 ***	VAPOR	+/-15.035	4.000

* - Unstable boiling
** - Q calculated from oxygen test data
*** - Oxygen flow rate calculated from Q calculated from hydrogen test data

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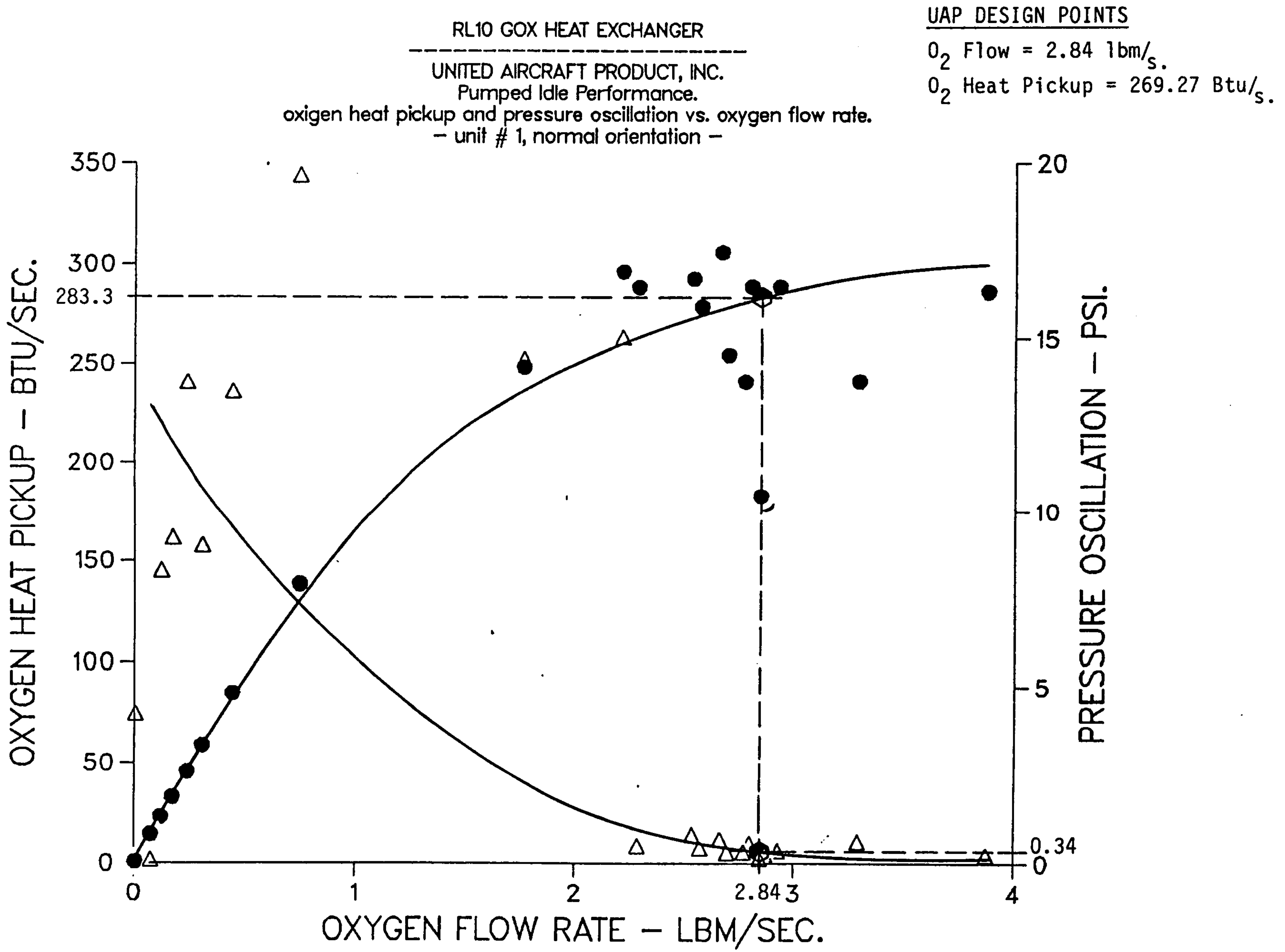

GRAPH - C1.

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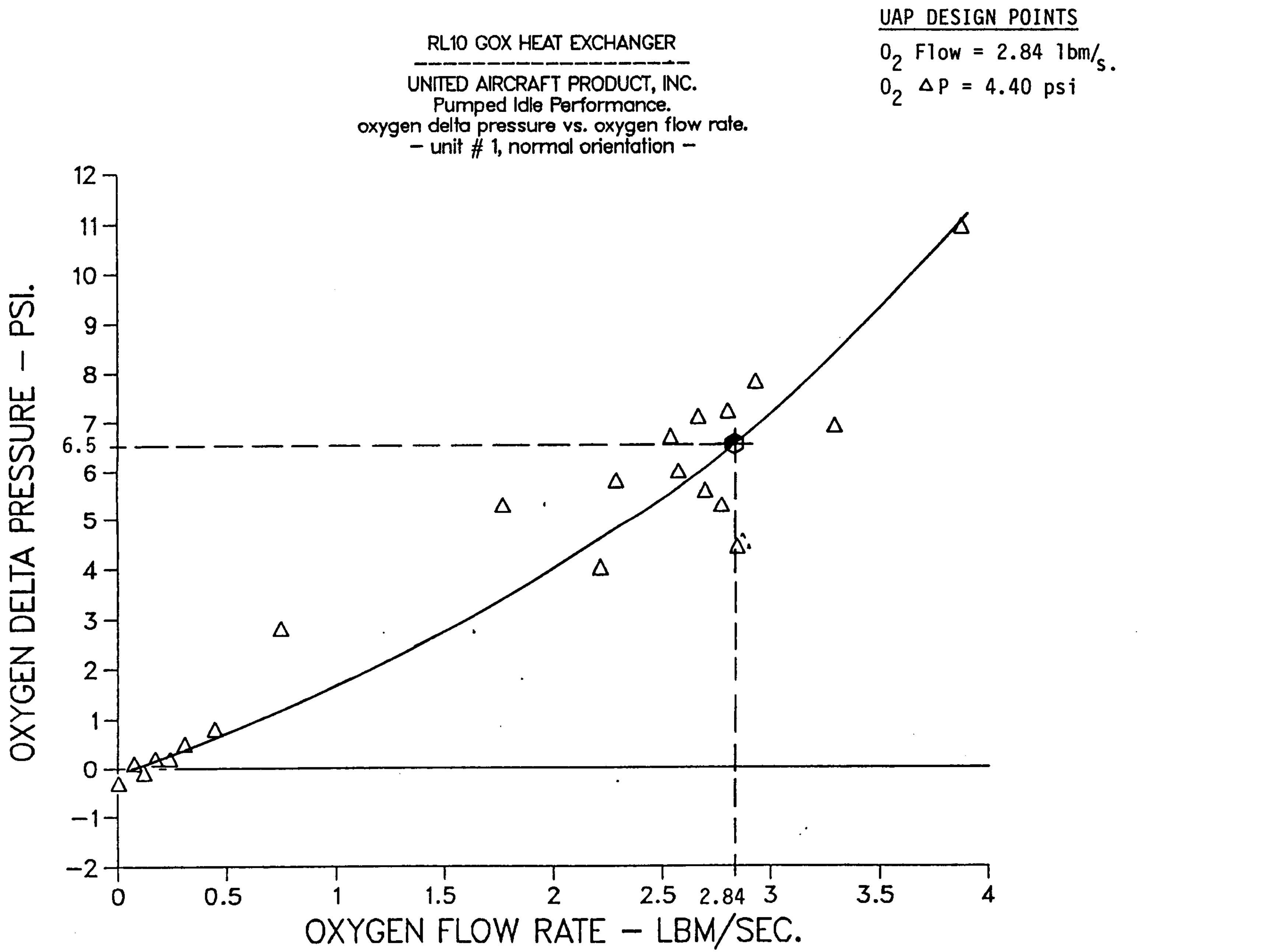

UAP DESIGN POINTS
O_2 Flow = 2.84 lbm/s.
O_2 ΔP = 4.40 psi
RL10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
Pumped Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit # 1, normal orientation –
OXYGEN DELTA PRESSURE – PSI.
12
11
10
9
8
7
6.5
6
5
4
3
2
1
0
−1
−2
0
0.5
1
1.5
2
2.5
2.84
3
3.5
4
OXYGEN FLOW RATE – LBM/SEC.

GRAPH - C2.

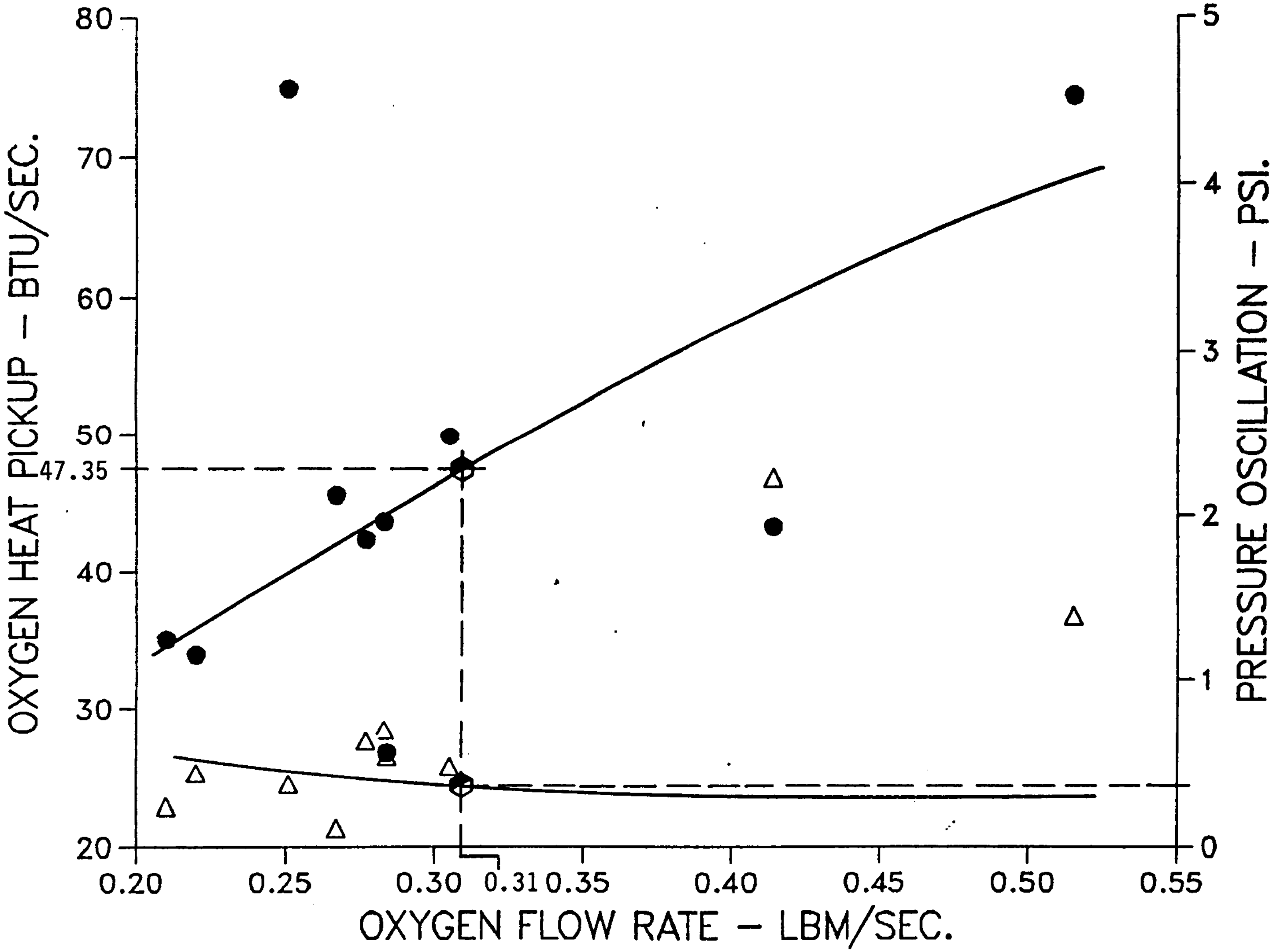
RL10 GOX HEAT EXCHANGER

UNITED AIRCRAFT PRODUCT, INC.
Tank Head Idle Performance.
oxygen heat pickup and pressure oscillation vs. oxygen flow rate.
– unit # 1, normal orientation –

UAP DESIGN POINTS

O_2 Flow = 0.31 lbm/s.

O_2 Heat Pickup = 56.95 Btu/s.



GRAPH - C3.

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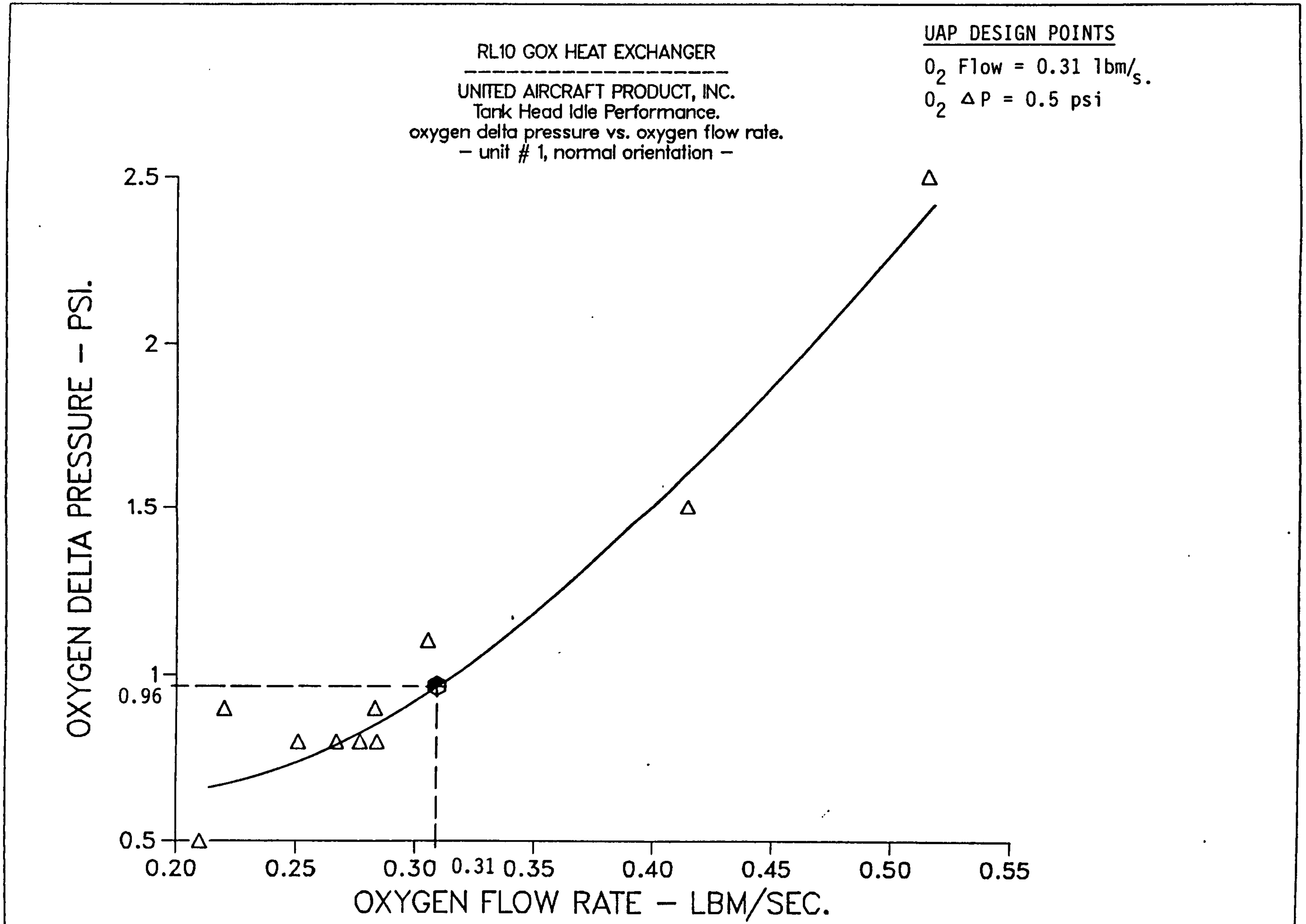

GRAPH - C4.

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TABLE C3

RL10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
(HYDROGEN CIRCUIT)
- UNIT #2 -

TEST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	ΔP (psi)	Q (Btu/s)	Flow Rate (lbm/s)
(PUMPED IDLE - NORMAL ORIENTATION)							
1 *	639.9	33.8	604.9	31.5	2.30	22.9	0.188
2 *	639.8	34.5	594.1	32.1	2.40	30.9	0.194
3 *	639.3	33.8	584.1	31.4	2.40	36.8	0.191
4 *	638.8	33.2	576.2	30.9	2.30	41.5	0.190
5 *	639.1	33.3	552.6	31.0	2.30	58.7	0.194
6 *	637.5	32.8	532.8	30.4	2.40	71.3	0.194
7 *	637.5	31.7	497.0	29.5	2.20	94.1	0.190
8 *	637.0	29.3	396.0	27.4	1.90	162.1	0.193
9 *	636.5	26.3	271.5	24.6	1.70	259.3	0.193
10	636.0	24.2	219.8	22.8	1.40	293.6	0.191
11	635.4	24.3	223.8	22.9	1.40	291.9	0.192
12	647.9	20.9	207.8	19.9	1.00	252.8	0.156
13	653.2	17.6	187.3	17.1	0.50	181.1	0.106
14	642.7	23.2	219.7	21.8	1.40	287.1	0.184
15	635.7	25.8	236.8	24.0	1.80	306.5 ▲	0.208
16	638.1	23.8	221.6	22.3	1.50	293.7 ▲	0.191
(TANK HEAD IDLE - INVERTED ORIENTATION)							
17	596.8	16.2	478.2	16.0	0.20	16.9	0.040
18	599.4	18.9	525.2	18.2	0.70	18.6	0.071
19	601.3	24.1	549.1	22.9	1.20	20.6	0.112
20	601.9	25.8	556.7	24.4	1.40	19.4	0.122
21	599.3	23.0	551.8	21.9	1.10	17.2	0.103
22	602.9	15.1	381.2	15.1	0.00	15.3	0.019

* - Unstable boiling

▲ - Disagreement between oxygen and hydrogen heat load, the heat load from hydrogen was used to generate graphs

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TABLE C4

RL10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
PERFORMANCE TEST DATA
(OXIDIZER CIRCUIT)
- UNIT #2 -

TEST POINT	T Oin (R)	P Oin (psia)	T Oout (R)	P Oout (psia)	ΔP (psi)	Q (Btu/s)	Flow Rate (lbm/s)	Exit Quality	Pressure Oscillation (psi)
(PUMPED IDLE - NORMAL ORIENTATION)									
1 *	167.1	89.4	641.1	89.2	0.20	22.9	0.118 ***	VAPOR	+/- 6.873
2 *	167.3	88.6	641.2	88.3	0.30	30.9	0.159 ***	"	+/- 8.784
3 *	167.2	89.9	641.6	89.7	0.20	36.8	0.189 ***	"	+/-12.062
4 *	166.9	90.2	642.4	89.7	0.50	41.5	0.213 ***	"	+/- 9.078
5 *	167.2	89.2	642.2	88.5	0.70	58.7	0.301 ***	"	+/-12.042
6 *	166.9	89.5	640.5	88.8	0.70	71.3	0.367 ***	"	+/-10.952
7 *	166.9	88.2	636.1	86.5	1.70	94.1	0.486 ***	"	+/-18.534
8 *	176.9	84.5	582.2	79.3	5.20	162.1	0.914 ***	"	+/-17.497
9 *	169.4	83.3	302.0	75.2	8.10	259.3	2.192 ***	VAPOR	+/- 8.416
10	165.7	82.9	195.3	70.6	12.30	293.6	3.828	78%	+/- 0.300
11	165.9	84.0	196.0	72.5	11.50	291.9	3.510	VAPOR	+/- 0.577
12	166.0	86.5	198.9	80.0	6.50	252.8	2.810	94%	+/- 0.353
13	166.7	85.7	198.9	80.7	5.00	181.1	3.112	55%	+/- 0.177
14	166.9	86.2	198.3	78.3	7.90	287.1	2.904	VAPOR	+/- 0.232
15	167.1	87.6	232.0	80.7	6.90	245.7 **	2.387	"	-/- 0.480
16	166.9	92.0	201.7	85.3	6.70	244.0 **	1.571	"	+/- 0.188
(TANK HEAD IDLE - INVERTED ORIENTATION)									
17	173.7	27.4	596.8	27.2	0.20	16.9	0.093 ***	VAPOR	+/- 3.197
18	173.8	27.2	600.6	26.9	0.30	18.6	0.196 ***	"	+/- 5.065
19	174.4	27.5	598.2	27.3	0.20	20.6	0.219 ***	"	+/- 7.350
20	175.6	28.9	600.8	28.7	0.20	19.4	0.206 ***	"	+/- 6.331
21	174.5	27.9	601.8	17.6	0.30	17.2	0.181 ***	"	+/- 3.863
22	173.6	26.5	594.8	26.3	0.20	15.3	0.164 ***	"	+/- 4.627

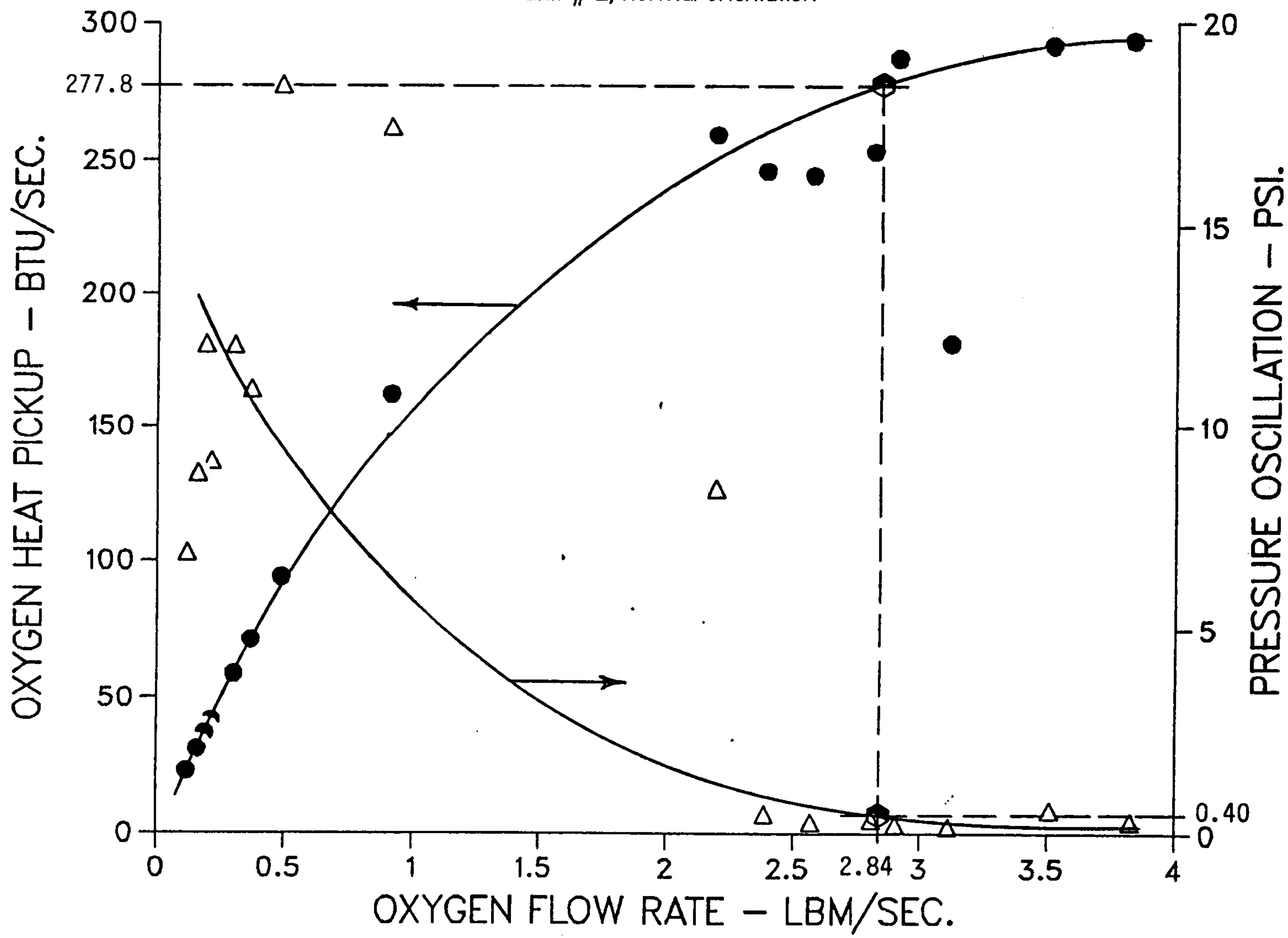
* - Unstable boiling
** - Q calculated from oxygen test data
*** - Oxygen flow rate calculated from Q calculated from hydrogen test data

RL10 GOX HEAT EXCHANGER

UNITED AIRCRAFT PRODUCT, INC.
Pumped Idle Performance.
oxigen heat pickup and pressure oscillation vs. oxygen flow rate.
— unit # 2, normal orientation —

UAP DESIGN POINTS

O_2 Flow = 2.84 $Lbm/_s$.
O_2 Heat Pickup = 269.27 $Btu/_s$.



GRAPH - C5.

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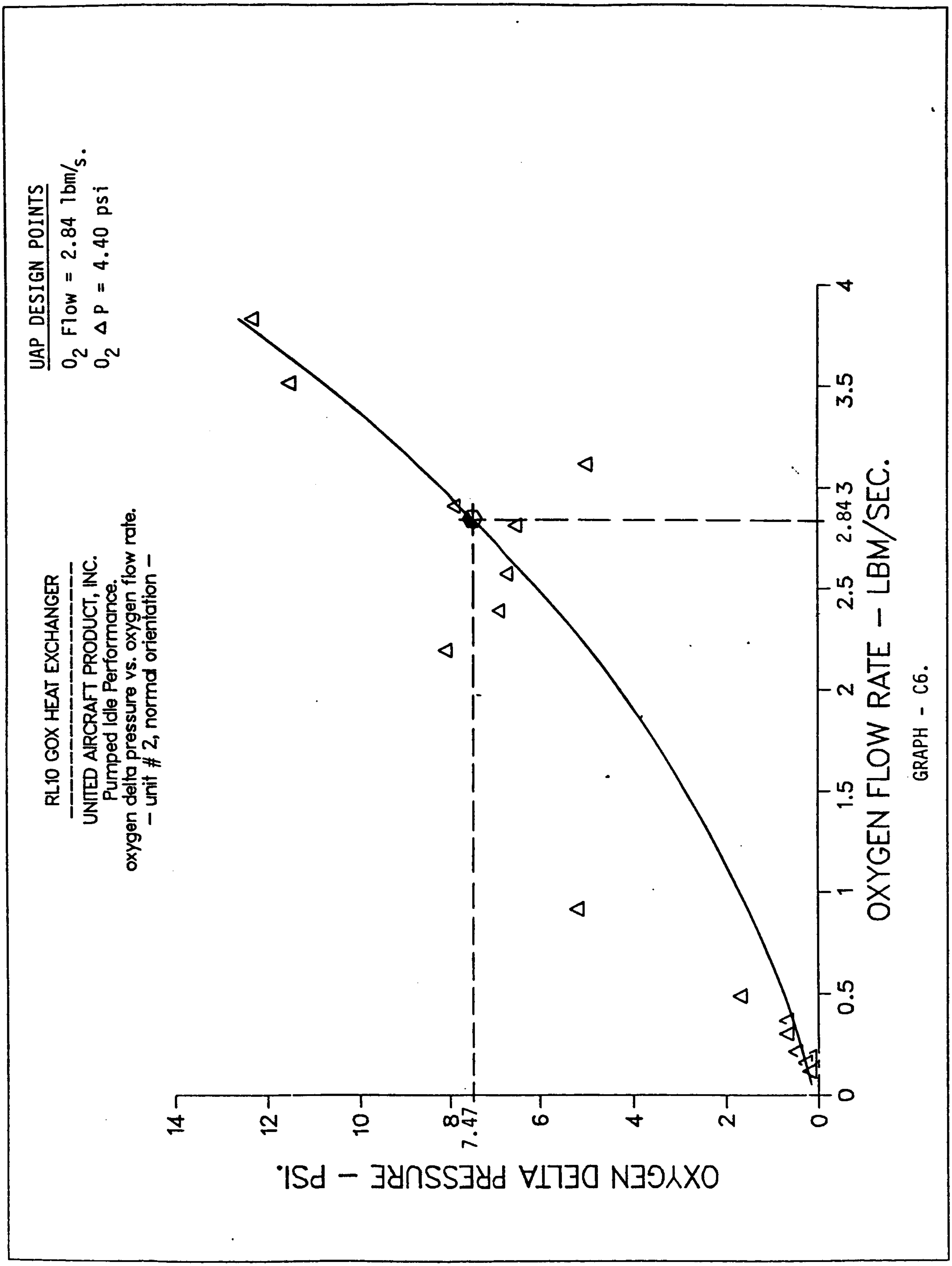

RL10 GOX HEAT EXCHANGER
UNITED AIRCRAFT PRODUCT, INC.
Pumped Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit # 2, normal orientation –
UAP DESIGN POINTS
O_2 Flow = 2.84 lbm/s.
O_2 Δ P = 4.40 psi
OXYGEN DELTA PRESSURE – PSI.
14
12
10
8
7.47
6
4
2
0
0
0.5
1
1.5
2
2.5
2.84
3
3.5
4
OXYGEN FLOW RATE – LBM/SEC.
GRAPH - C6.

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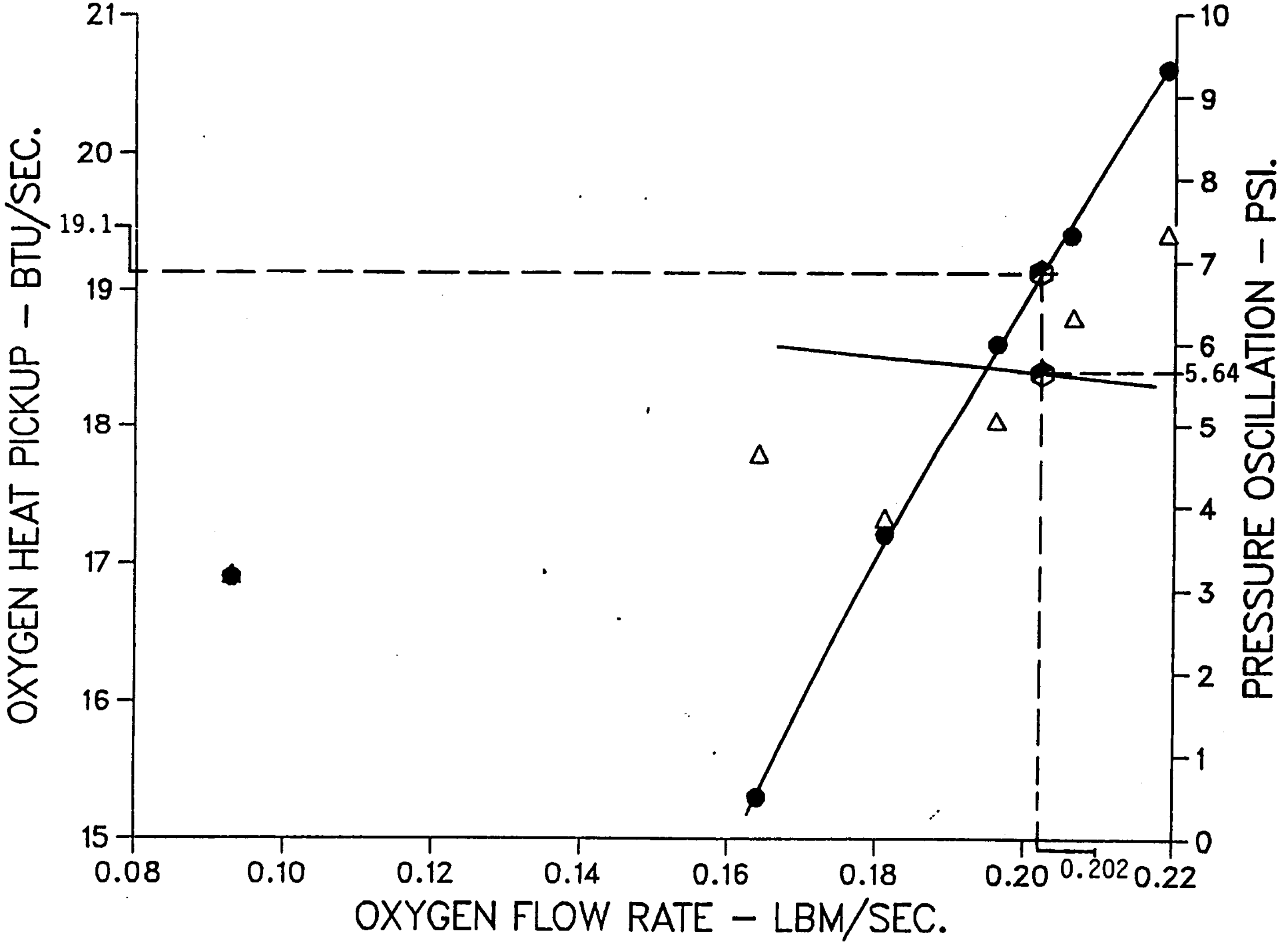
RL10 GOX HEAT EXCHANGER

UNITED AIRCRAFT PRODUCT, INC.
Tank Head Idle Performance.
oxygen heat pickup and pressure oscillation vs. oxygen flow rate.
– unit # 2, inverted orientation –

UAP DESIGN POINTS

O_2 Flow = 0.31 $Lbm/_s$.
O_2 Heat Pickup = 56.95 $Btu/_s$.



GRAPH - C7.

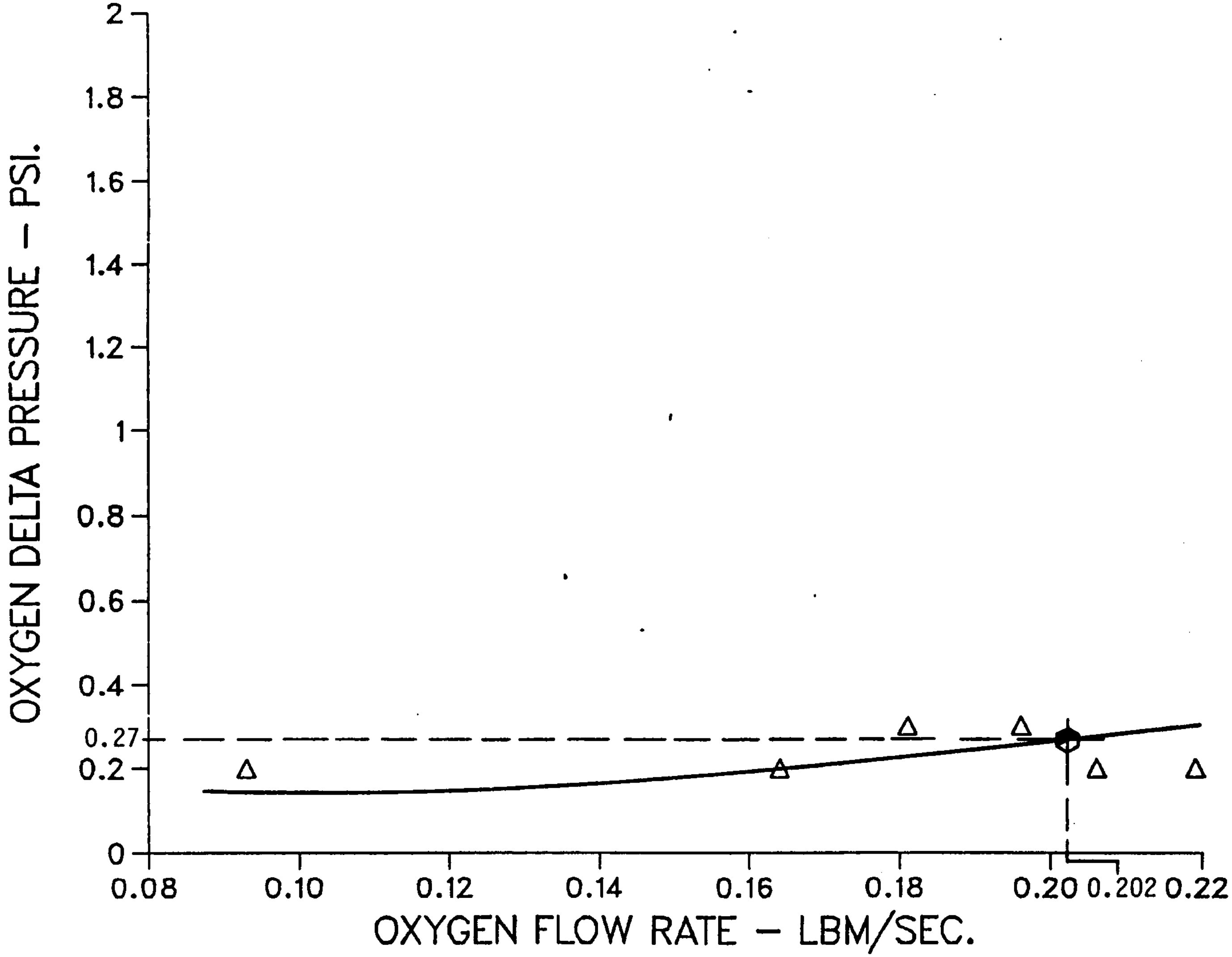
RL10 GOX HEAT EXCHANGER

UNITED AIRCRAFT PRODUCT, INC.
Tank Head Idle Performance.
oxygen delta pressure vs. oxygen flow rate.
– unit # 2, inverted orientation –

UAP DESIGN POINTS

O_2 Flow = 0.31 Lbm/s.

O_2 ΔP = 0.5 psi



GRAPH - C8.

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15. Supplementary Notes

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16. Abstract

The RL10-IIB engine, a derivative of the RL10, is capable of multimode thrust operation. This engine operates at two low-thrust levels: tank head idle (THI), approximately 1 to 2 percent of full thrust, and pumped idle (PI), 10 percent of full thrust. Operation at THI provides vehicle propellant settling thrust and efficient engine thermal conditioning; PI operation provides vehicle tank prepressurization and maneuver thrust for low-g deployment.

Stable combustion of the RL10-IIB engine during the low-thrust operating modes can be accomplished by using a heat exchanger to supply gaseous oxygen to the propellant injector. The oxidizer heat exchanger (OHE) vaporizes the liquid oxygen using hydrogen as the energy source. This report summarizes the test activity and post-test data analysis for two possible heat exchangers, each of which employ a completely different design philosophy. One design makes use of a low-heat transfer (LHT) core to promote stable oxygen vaporization; the other design uses a high-heat transfer (HHT) approach in combination with a volume to attenuate pressure and flow oscillations. The test data showed that the LHT unit satisfied the oxygen exit quality of 0.95 or greater in both the THI and PI modes while maintaining stability. The HHT unit fulfilled all PI requirements; data for THI satisfactory operation is implied from experimental data that straddle the exact THI operating point.

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